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Composite Load Spectra for Select Space Propulsion Structural Components
(Third Annual Report)

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Abstract

The objective of this program is to develop generic load models with multiple levels of progressive sophistication to simulate the composite load spectra that are induced in space propulsion system components, representative of Space Shuttle Main Engines (SSME), such as transfer ducts, turbine blades, and liquid oxygen (LOX) posts and system ducting. These models will be developed using two independent approaches. The first approach will consist of using state-of-the-art probabilistic methods to describe the individual loading conditions and combinations of these loading conditions to synthesize the composite load spectra simulation. The methodology required to combine the various individual load simulation models (hot-gas dynamic, vibrations, instantaneous position, centrifugal field, etc.) into composite load spectra simulation models will be developed under this program. A computer code incorporating the various individual and composite load spectra models will be developed to construct the specific load model desired.

The second approach, which is covered under the options portion of the contract, will consist of developing coupled models for composite load spectra simulation which combine the (deterministic) models for composite load dynamic, acoustic, high-pressure and high rotational speed, etc., load simulation using statistically varying coefficients. These coefficients will then be determined using advanced probabilistic simulation methods with and without strategically selected experimental data.

This report covers the efforts of the third year of the contract. The overall program status is that the turbine blade loads have been completed and implemented. The transfer duct loads are defined and are being implemented. The thermal loads for all components are defined and coding in work. A dynamic pressure load model is under development. The parallel work on the probabilistic methodology is essentially completed. The overall effort is being integrated in an expert system code specifically developed for this project.

1.0 INTRODUCTION

1.1 General

Requirements for better performance and longer life have pushed engine designs to lighter weight systems, higher reliability, and increased pressures and environments. Temperatures, external and internal fluids flow noise, and mechanical vibration levels have increased markedly and have been shown to limit the hardware designs. Advanced engine concepts and designs are different enough that the loads cannot be simply scaled from other engines.

The use of engine cycles such as staged combustion on the SSME result in engine operating pressures in the 3000 to 7000 psi regime. High performance turbomachinery operate in the 30,000 to 100,000 RPM regime. These operational requirements result in complex high energy loading throughout the engine. The difficulty in installation, cost, and the potential for destroying an engine has severely limited the required instrumentation and measurements to adequately define loads of key components such as turbine blades. Also, accurate analytical methodologies for defining internal flow-related loads are just emerging for problems typically found in rocket engines. The difficulty of obtaining measured data and verified analysis methodologies has led to the probabilistic load definition approach of this contract.

Current loads analyses methodologies are driven by their usage in deterministic analysis methods. This includes strength and fatigue analysis as well as mechanical vibration. The deterministic solution typically uses an upper bound approach where maximum loads and minimum properties are used. For critical hardware, a separate sensitivity study is often made to determine more nominal operation and which loads and their variation govern the hardware design, but quantification of the actual variations and their frequency of occurrence is a crucial weakness.

The Composites Loads Spectra Contract (CLS) and the associated Probabilistic Structural Analysis Method (PSAM) contract from Lewis Research Center are developing an integrated probabilistic approach to the structural problem. The probabilistic loads approach has the ability to more technically quantify knowledge relative to the loads. The use of mean values and distribution about this central value rather than the maximum or enveloped loads can add greatly to the understanding of normal engine operation and still furnish as good or better knowledge of maximum conditions.

The present techniques often result in manufacturing of components that in many cases greatly exceed design requirements, but there is no way of assessing this margin for extending the useful life margin. Thus, to formulate more effective designs, it is necessary that the loads on the components of rocket engines be derived so that they can be applied by probabilistic analysis methods such as PSAM to end up with results that are quantifiable to more accurately reflect the true risk. The SSME engine is currently undergoing a failure modes and effect analysis. The assessment would be much easier to perform if a probabilistic analysis and associated risk assessment were available.

This project will provide methods to combine technologies of analytical (deterministic) loads and probabilistic modeling. Since these methods will be developed from a generic approach, they will be applicable to current or advanced liquid rocket engine designs.

1.2 Project Objective

The objective of this program is to develop generic load models with multiple levels of progressive sophistication to simulate the composite (combined) load spectra that are induced in space propulsion system components, representative of Space Shuttle Main Engines (SSME), such as transfer ducts, turbine blades, and liquid oxygen (LOX) posts and systems ducting. The approach will consist of using state-of-the-art probabilistic methods to describe the individual loading conditions and combinations of these loading conditions to synthesize the composite load spectra simulation.

The methodology required to combine the various individual load simulation models (hot-gas, dynamic, vibrations, instantaneous condition, centrifugal field, etc.) into composite load spectra simulation models will be developed under this program. Results obtained from these models will be compared with available numerical results, with the loads induced by the individual load simulation models, and with available structural analysis results from individual analyses and tests. These theories developed will be further validated with respect to level of sophistication and relative to predictive reliability and attendant level of confidence.

A computer code incorporating the various individual and composite load spectra models is being developed to construct the specific load model desired. The approach is to develop incremental versions of the code. Each code version will add sophistication to the component probabilistic load definition and the decision making processes, as well as installing a new set of loads for an additional component. This allows for ongoing evaluation and usage of the system by both Rocketdyne and NASA.

2.0 SUMMARY

The development of probabilistic generic load models is a 3 1/2 year base program and a 2 year option program. Rocketdyne is responsible for the overall project. Battelle Columbus Laboratories (BCL) is the major subcontractor for developing the probabilistic load models and related tasks. The effort is divided into three tasks: probabilistic model development, code development and code validation and verification. The previous reports on this project (Ref. 1 & 2) presented the survey and basis for the load definitions and probabilistic analysis, development of the first code version, implementation of the steady state engine model and elements of the turbine blade loads. This model had the essential features of the expert system and overall probabilistic loads.

The SSME is being used as a baseline model for defining the loads and requirements. The SSME configuration of the 4 components studied are shown in Figures 1-2. Figure 1 is a cross-section of the SSME powerhead showing typical LOX posts in the three combustors (2 preburners and the main injector), transfer ducts between the turbines and the main injector and turbine blades.

Figure 2 shows the HPOTP discharge duct in an overall SSME powerhead view. This duct was chosen as the 4th component because of its history of fluid vibration related problems. A methodology for high energy flow vibration environments is being developed as part of this contract for the analysis of this class of hardware. Table 1 is a matrix of the individual loads addressed by this project, the components where the loads have significant effects and the form of the load for inputing in an analysis. The current status of the individual load definition, and implementation in the expert system

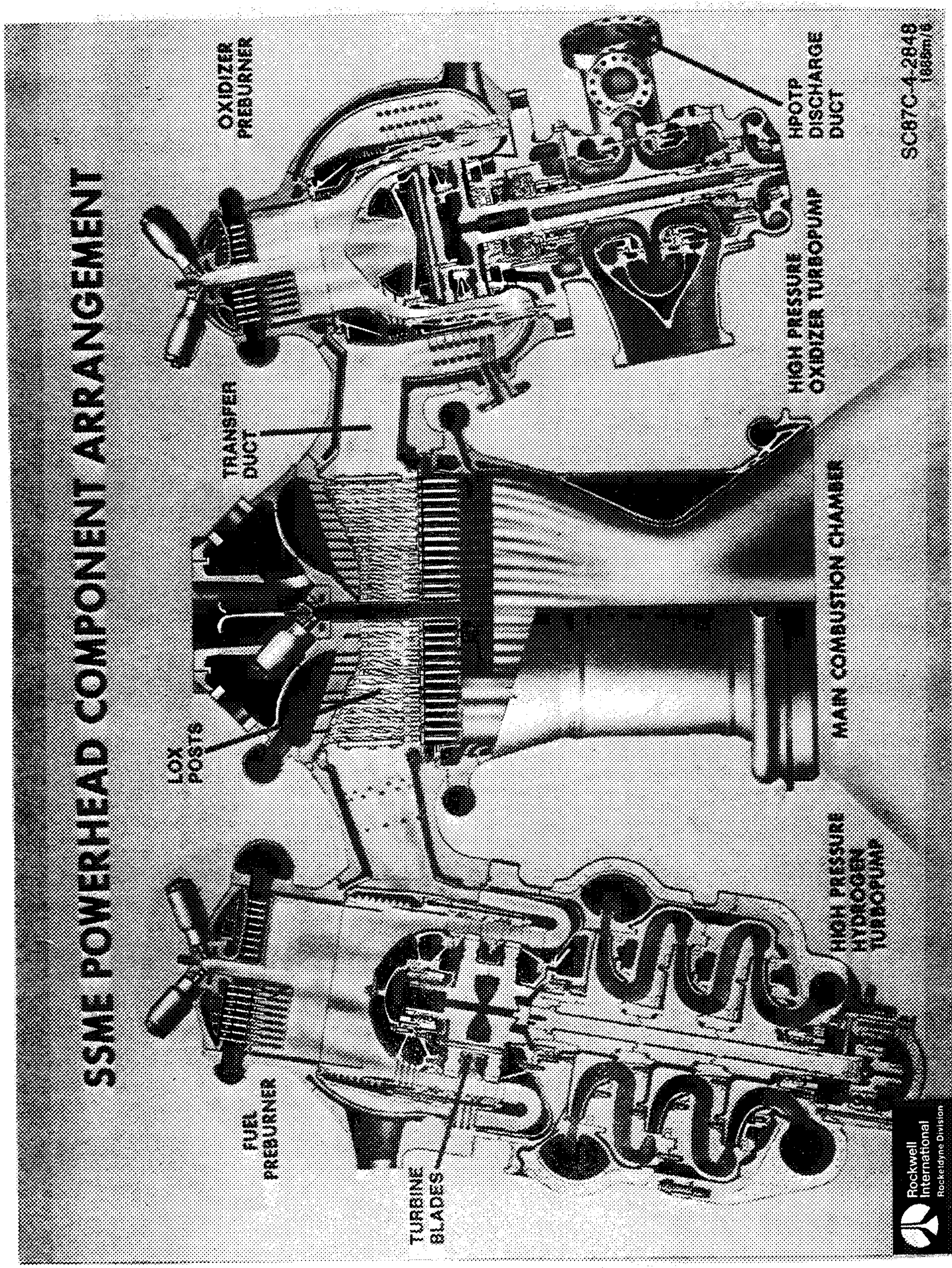

Figure 1. SSME Powerhead With LOX Posts, Transfer Ducts and Turbine Blades Identified

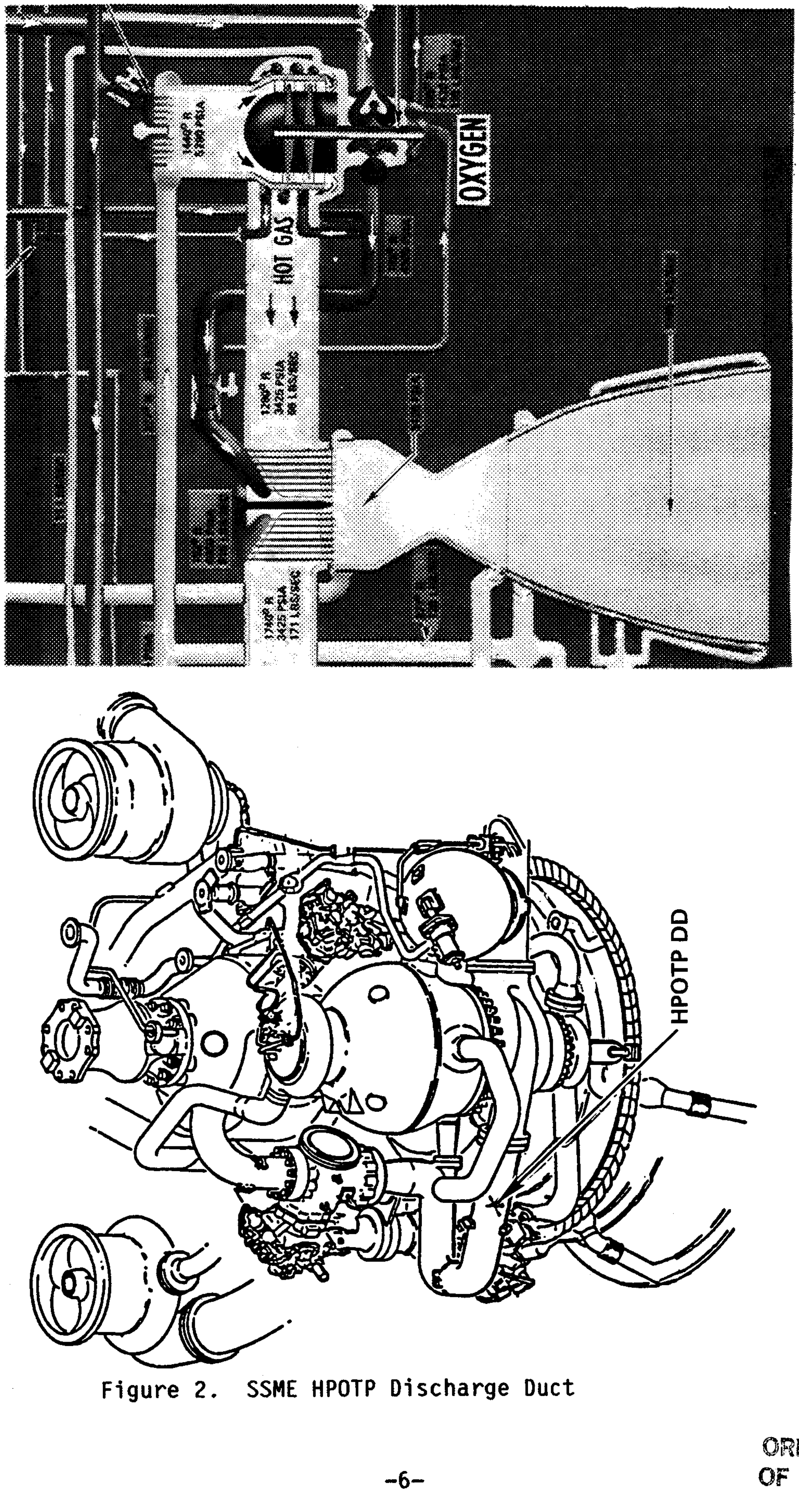

Figure 2. SSME HPOTP Discharge Duct

Table 1. Summary Matrix of Individual Loads vs. Components

INDIVIDUAL LOAD	TURBINE BLADE	TRANSFER DUCT	LOX POST	HPOTPDD	LOAD FORM/ TEST DATA FORMAT
• STATIC PRESSURE	X	X	X	X	DUTY CYCLE
• DYNAMIC PRESSURE					
• CHUGGING (TRANSIENT)	–	X	–	–	AMS, STATOS
• TURBULENCE					
• SINUSOIDAL (REPEATED PULSE)	X				AMS, PSD, STATOS
• RANDOM	–	X	X	X	AMS, PSDS
• CENTRIFUGAL	X	–	–		DUTY CYCLE
• TEMPERATURE	X	X	X	X	DUTY CYCLE
• STRUCTURAL VIBRATION					
• TRANSIENT					
• SIDELOAD	–	X	X	X	AMS, STATOS
• POPS	–	X	X	–	AMS, STATOS
• STEADY STATE					
• SINE	–	X	X	X	AMS, PSD, STATOS
• RANDOM	–	X	X	X	AMS, STATOS
• DEBRIS	X	X	X	–	HISTORY
• RUBBING	X	–	–	–	EXPERT OPINION

Operational in LDEXPT

Load Definition Completed
Implementation in Work

Load Definition in Progress

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are also noted. The turbine blade model is defined and implemented in the code (except for repeated pulse loads that are currently being summarized). The transfer duct model is defined and implementation in the expert system is underway.

All of the thermal loading has been defined and is being implemented in the code. The dynamic pressure loads for 2 components are ready for code implementation and the remaining loads are in work.

The probabilistic load development has proceeded in parallel with the load definition work. The goal is to be able to address generic engines that may include different mission profiles or incorporate design changes. This requires a robust and general probabilistic approach be adopted for inclusion in the expert system model. The methodology is essentially complete. The steady state operation model was implemented in an earlier version of the code. The transient model has been implemented in the current version of the code. Pulse and random loading development has been the last primary load types and are being defined. The probabilistic model has 3 methods: 1) second moment method which assumes that all load variables and parameters are normally distributed, 2) discrete probability method (RASCAL) and 3) Monte Carlo.

Details of this work are found either in previous project reports or this report that summarizes the current work. The final report will include a theory and background manual, user manual and systems manual that covers essential work of the entire project.

This years report is primarily an overview of the work accomplished in the last year. The report is organized to first discuss engine loads-system, components and individual load components, the probabilistic load development and finally the expert system code development. Figure 3 shows how this overall effort is integrated together into the LDEXPT expert system code.

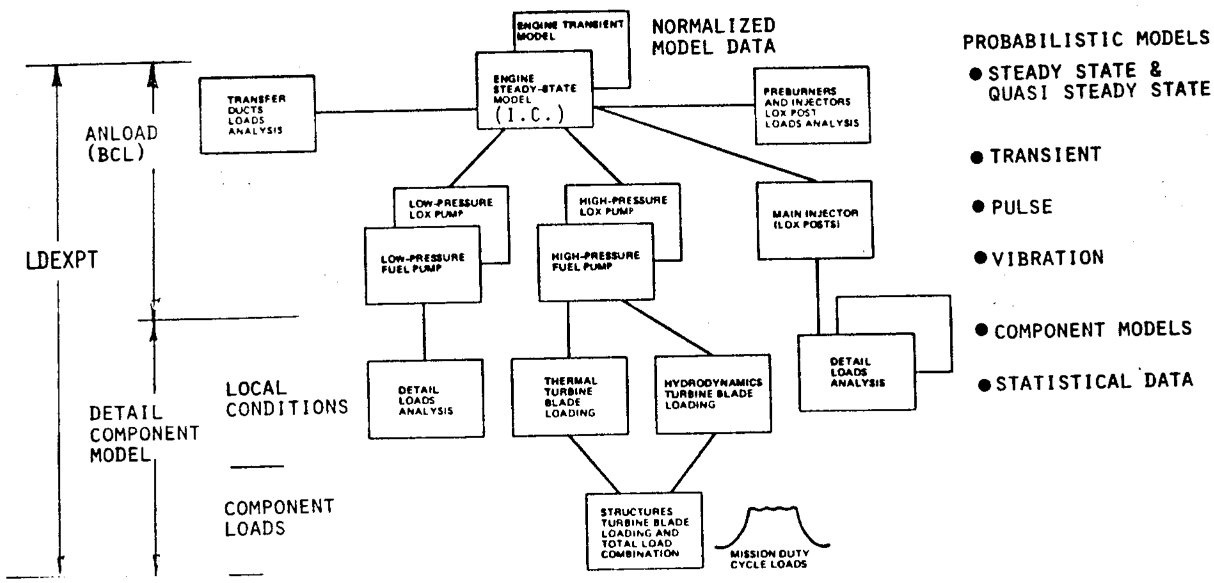

Figure 3. Modeling and Code Effort

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3.0 Engine Loads

3.1 General

The load definition for the four components is approached from several ways depending on the individual load (pressure, temperature, vibration) and the component. The majority of these individual loads require information relative to the engine power level or information at major component interfaces (i.e. turbine and pump interfaces for turbine blades).

This information must be presented in a duty cycle format to address the total engine operation. Changes in duty cycle and loads must be accommodated. This led to the implementation of an engine model based on an influence coefficient (IC) method that is developed from a standard engine performance model. This model is applicable to steady state or quasi-steady state engine operation. Inputs to the model are both deterministic and/or mean duty cycle information and random variations of engine inlet conditions, thrust level, etc.

3.2 Engine Steady State and Quasi-Steady State Model

The Composite Loads Contract (CLS) effort has implemented a method using engine influence coefficients with random variations and direct variables as independent parameters for defining a generic approach to calculating dependent loads. The influence coefficient methodology has gradually evolved through each version of the code and the ongoing probabilistic load development at Battelle and Rocketdyne.

The key need for the CLS work is to have a general methodology (generic) that can be applied equally as well to the SSME and other advance engines that may be considerably different, not just simply scaled versions of the SSME. These engines could have different engine cycles, pumps, etc. The influence coefficient approach recognizes the fact that some overall system model is always available to develop these coefficients - even in the conceptual stage of an engine development. The influence coefficient form is a simplified model that can be developed from this system model. Influence coefficients are a deliverable item and are used for flight performances data analysis. This model form is cost effective to run and can be readily adapted to a probabilistic approach. Being developable from a specific engine allows major changes to the engine model description that interfaces with probabilistic code. The SSME influence coefficient model was chosen as the baseline engine model for the CLS work. The phase I model allows variation of 20 engine independent parameters to calculate the duty cycle operating conditions at selected locations throughout the engine. The SSME phase II model, modified for CLS use, allows for approximately 50 independent parameters and 100 dependent parameters.

3.3 Generic Random Variables

The SSME Engine was the first time that Rocketdyne developed a series of random variables that accounted for variations in hardware and testing. The variations were based on consultations with component experts to define how much each item was expected to vary from a manufacturing, performance, or test to test basis. The performance unit then combined this with design requirements and their own knowledge of past engine performance to develop a set of over 40 random variables. The combined effect of these variables are used in the definition of max/min conditions used for the engine balance limits. The calculated variations can be checked through comparing actual measured variations of the instrumented parameters of the engine to gain confidence in the accuracy of the overall system response variations. Checking of this type has been done by the performance unit. The current set is still essentially the same as estimates made almost 15 years ago. Today, a somewhat different set might be used and better estimates could be made by the component specialists based on the SSME experience base. Work is currently underway to update and establish these variations.

These random variables assigned to specific engine components are the essence of the options approach to load definition. Estimated variations of components can be assigned to old, similar or new components. Using these variations in a probabilistic load model results in probabilistic estimates of load variations throughout the engine.

The use of the random variables in the current SSME approach is to combine the engine to engine and test to test variation into a single range of two sigma variation. The SSME approach also adds in a variation for contract limit conditions for "direct loads" like engine inlet conditions that extends the max/min bounds to a wider band about the nominal operating conditions. This information is used for design purposes as well as a bounds check that engine operation is satisfactory to continue into another test or flight. Using these overall bounds is not very usable in assessing the accuracy of the model for the CLS work.

The approach generally used to compare engine performance from engine to engine or calibrate the engine model is to normalize each test by perturbing engine independent variables such that they simulate a standard baseline set of values. This approach has worked quite well, but it does not project actual operating conditions in a test. Trend charts that typically relate an engine parameter versus power level have recently been implemented on SSME for data analysis of actual operating conditions. The trend bounds are based on statistical estimates based on a series of tests and are used to demonstrate that specific variables fall within a reasonable bound during engine operation. Another viable approach is the probabilistic CLS methodology using the influence coefficient model. This method can be used to assess engine operation bounds and project duty cycle loads for new test conditions.

For the CLS work the random variables are considered independent loads categorized as an effect on either engine to engine or test to test operation or both. The direct independent loads will also be used as duty cycle discrete values with random variations rather than a limit box for bounds determination. The SSME approach has been consistent with the deterministic analyses constraints. The CLS approach is consistent with the generic probabilistic approach of this project for defining a more quantifiable load variation, not just limit conditions.

3.4 Methodology Implementation and Evaluation

Battelle incorporated the SSME phase I production set of coefficients and random variables into the ANLOAD probabilistic code and has made validation and verification studies of the analysis method using the SSME 10SECR database and the ANLOAD probabilistic load code. The HPFTP speed variation was compared from measured values versus the probabilistic calculation procedure. Previously, Battelle had calculated the HPFTP discharge temperature and had limited success in comparing the results with actual test data variations. Since there probably is significant measurement error in this variable, it was thought that this could have been a major contributor to the difference in the answers. Therefore, a pump speed measurement was chosen for the next evaluation since it should have about the best measurement accuracy. The comparison of the measured vs. calculated variation on pump speed again showed significant error.

The production influence coefficients model is essentially a nominal engine model that uses independent conditions - inlet pressures and temperatures, thrust, etc. - for some 20 variables - to calculate dependent variables used to assess engine performance. The individual coefficients of the influence coefficients model related to engine variables such as duct or pump resistances and pump head rise. This model form, where coefficients are not perturbed, is consistent with the baseline CLS code work. To account for an "as built" engine condition, the performance unit calculates "tag" values based on the engine acceptance tests that adjust the nominal values of the independent variables. This essentially furnishes a deterministic adjustment of the influence coefficients to accurately depict the as built condition.

Another way of looking at the production influence coefficients model is that it only accounts for test to test or variations of variables within a test. The engine to engine variations are accounted for by changing the nominal values of the independent variables, i.e. using the tag values.

From the CLS standpoint, the production influence coefficients with nominal independent variables may be sufficient for some of the loads for the 4 components under study, but it's not adequate for certain variables such as pump speed. The as built condition of a particular pump causes too much variation to ignore. Two possible approaches were available to account for the engine to engine as built conditions: 1) use the tag values as variables, or 2) add probabilistic variation to the influence coefficients.

The tag value approach could be readily implemented, since estimates can either be made from expert opinion or readily available engine data can be used to determine statistical variations from ground test and flight engine. The problem with this technique is that these variations are not directly relatable to a specific engine component as built condition. This makes the modeling very dependent on the SSME engine and looses the generic approach.

The second approach, which is consistent with the option phase of the CLS contract, essentially addresses perturbing the influence coefficients constants to account for the as built - engine to engine - variations and is a generic approach since variations in resistance or head rise are basic parameters that are relatable to other engine models.

The basic problem with the production influence coefficients is that there is an insufficient number of independent variables to account for the component variations. The required added independent variables are essentially first order partial derivatives of the component coefficients. In addition, as will be discussed later, there are not enough dependent variables to calculate and perturb the various loads on the 4 components under study. Basically, the influence coefficients are for performance data of a nominal engine, not for load calculations.

Figure 4 puts the problem in perspective. The system class of loads can be divided into direct variables - controlled by the vehicle configuration and operation-and random variable that are either hardware or test to tests variables. The production IC used the direct variables and selected hardware variables that are known or adjusted to meet engine or vehicle performance requirements, e.g. low pressure fuel pump blockage or thrust coefficient. The hardware random variables for pumps or ducts or nozzles must be added as independent variables adjustments to account for engine to engine variation, i.e. probabilistic variation of individual terms the engine influence coefficients.

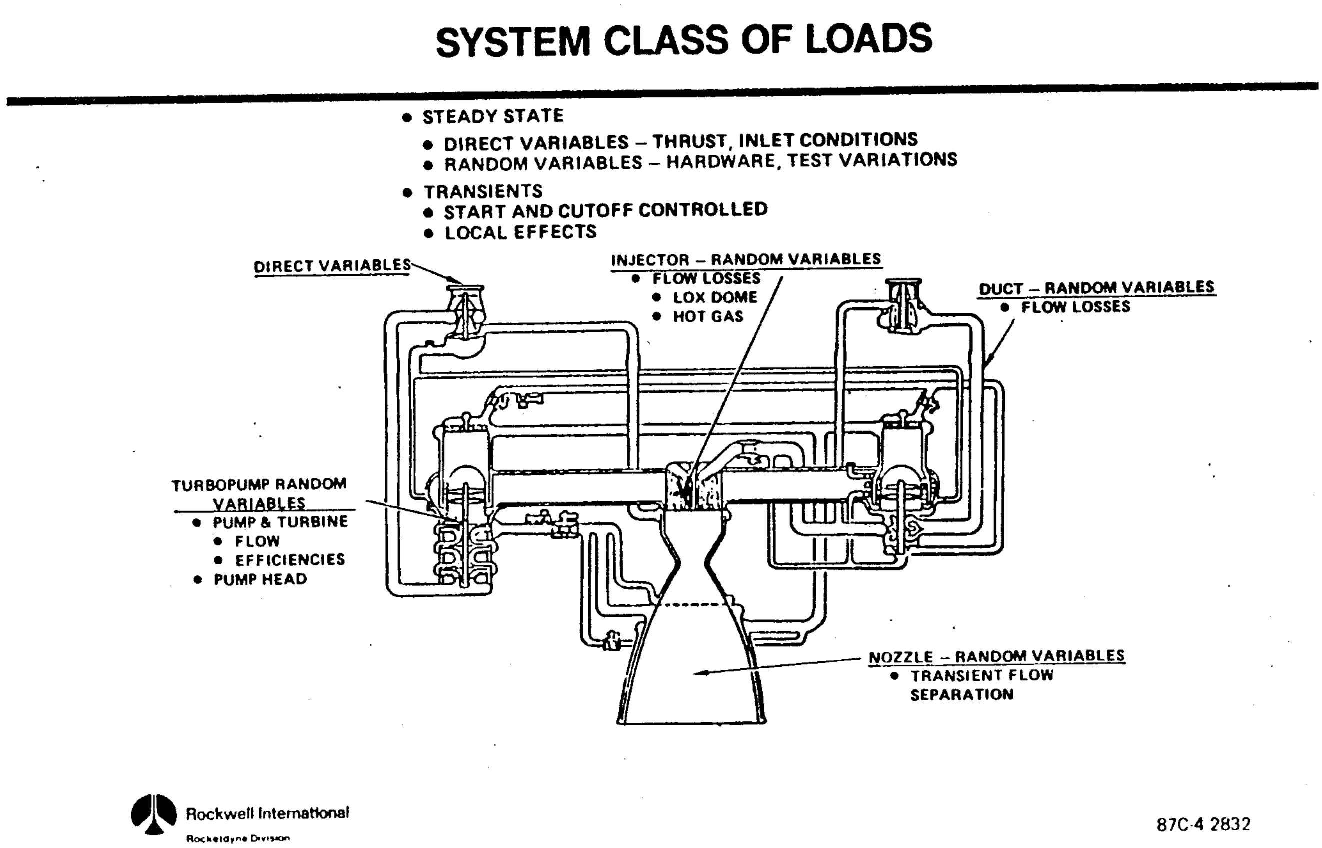


Figure 4. System Class of Loads

A detail study was made on which of the 46 hardware random variables (used by the performance unit) were significant for the CLS load definition. Table 2 lists the variables, the expected 2 sigma variation of each variable and the CLS related components that are significantly affected by the variable.

For instance, variation of the main chamber throat area, thrust or mixture ratio affects all the components, whereas variations of the LPOP or LPOT parameters only affect the LPO and the HPO turbopumps. In general, there is strong interaction of most of these hardware random variables on the CLS related components. So they should be included in the probabilistic model.

In parallel with this study, the total set of dependent variables that are required to calculate the complete set of component loads were determined. These variables are listed in Table 3. The type of added variables are pump power and combustor power for mechanical vibration loads, dynamic heads and velocity for pulsating flow loads.

A decision was made to go the generic random variable approach rather than the tag value approach. The development of the model which includes additional dependent variables required to perturb model coefficients was developed as part of the baseline CLS development effort. This expanded influence coefficients model will be implemented into the probabilistic model and expert system as the first task in the options phase of the contract. The direct and random independent variables are available for determining either engine to engine or test to test variations of the expanded set of dependent loads. The updated influence coefficients are consistent with Phase II SSME engine rather than the Phase I engine used with the initial production influence coefficients set. The Phase II engine is the flight configuration and is consistent with current SSME testing.

Verification of the methodology will be based on measured data from this version of the SSME.

Table 2. SSME Engine Model Random Variables

	VARIABLE NAME	2 σ VARIATION %	POWER HEAD	LPFTP	LPOTP	HPFTP	HPOTP	NOZZLE	HEAT EXCHANGER
1.	Main Chamber Throat Area	0.2	X	X	X	X	X	X	X
2.	Efficiency C_F (thrust coefficient)	0.2	X	X	X	X	X	X	X
3.	Efficiency C* (characteristic velocity)	0.25	X	X	X	X	X	X	X
4.	Chamber Coolant Resistance	8.0	X	X		X		X	
5.	Main Oxidizer Injector Resistance	5.0	X		X	X	X		X
6.	Main Hot Gas Injector Resistance	5.0	X			X	X	X	X
7.	FPB Fuel Injector Resistance	2.0	X			X	X	X	X
8.	OPB Fuel Injector Resistance	2.0	X			X	X	X	X
9.	Fuel Hot Gas Manifold Resistance	10.0	X	X		X	X	X	X
10.	LOX Hot Gas Manifold Resistance	10.0	X	X		X	X	X	X
11.	Main LOX Dome Resistance	4.0	X		X	X	X		X
12.	OP2 Discharge Duct Resistance (HPOT discharge press.)	4.0	X		X	X	X		X
13.	LPFT Nozzle Area	2.0	X	X		X	X	X	
14.	LPOP Efficiency	1.0			X		X		
15.	LPOT Efficiency	4.0			X		X		
16.	LPOT Nozzle Area	2.0			X		X		
17.	HPFP Efficiency	1.6	X	X	X	X	X	X	X
18.	HPFT Efficiency	2.0	X	X	X	X	X	X	X
19.	HPFT Nozzle Area	2.0	X	X	X	X	X	X	X
20.	HPOP Efficiency	0.8	X	X	X	X	X	X	X
21.	HPOT Efficiency	2.0	X	X	X	X	X	X	X
22.	HPOP Head Coefficient	0.8					X		
23.	HPFP Head Coefficient	1.6				X			
24.	HPOT Nozzle Area	2.0	X			X	X	X	
25.	Preburner Pump Efficiency	0.8					X		
26.	Preburner Pump Head Coefficient	0.8					X		
27.	Chamber Coolant Valve Resistance	17.6		X		X		X	
28.	Main LOX Valve Resistance	12.7			X		X		
29.	Main Fuel Valve Resistance	12.7		X		X			
30.	Primary Faceplate Resistance	15.0	X	X		X		X	
31.	Secondary Faceplace Resistance	15.0	X	X		X		X	
32.	MCC Baffles Resistance	6.6	X	X		X		X	
33.	Heat Exchanger Bypass Resistance	2.63*							X
34.	Heat Exchanger Tube Thickness A	8.5*							X
35.	Thrust	1.3	X	X	X	X	X	X	X
36.	Engine Mixture Ratio	1.0	X	X	X	X	X	X	X
37.	GOX Tank Press.	100.0*							X
38.	GH2 Tank Press.	100.0*	X					X	
39.	HPOP COV	5.0	X	X	X	X	X	X	X
40.	LPOP Head Coefficient	2.0			X				
41.	LPFP Head Coefficient	2.0		X					
42.	Nozzle Coolant Res.	8.0	X	X		X	X	X	X
43.	LPFT In Duct Res	4.0		X		X			
44.	LPOT Area	2.0			X		X		
45.	Nozzle ΔT	5.0	X	X		X		X	X
46.	MCC Coolant ΔT	8.0	X	X		X		X	X

*Note: not relevant to CLS work

Table 3. SSME Engine Influence Coefficient Dependent Parameters for CLS

1. HPOTP TURBINE SPEED (RPM)
2. HPFTP TURBINE SPEED (RPM)
3. HPOTP PUMP DISCHARGE PRESS.(PSIA)
4. HPFTP PUMP DISCHARGE PRESS.(PSIA)
5. OPB CHAMBER PRESSURE (PSIA)
6. FPB CHAMBER PRESSURE (PSIA)
7. ENGINE OXIDIZER FLOWRATE (LB/SEC)
8. ENGINE FUEL FLOWRATE (LB/SEC)
9. ENGINE THRUST (LB)
10. OXIDIZER PRESS. FLOWRATE (LB/SEC)
11. FUEL PRESSURANT FLOWRATE (LB/SEC)
12. OPB OXIDIZER VALVE POSITION
13. FPB OXIDIZER VALVE POSITION
14. MCC OXIDIZER INJECTOR PRESS (PSIA)
15. MCC OXIDIZER INJECTOR TEMP (R)
16. HOT GAS INJECTOR PRESSURE (PSIA)
17. MCC INJECTOR END PRESSURE (PSIA)
18. HPOTP PUMP INLET PRESSURE (PSIA)
19. HPFTP PUMP INLET PRESSURE (PSIA)
20. PB PUMP DISCHARGE PRESSURE (PSIA)
21. HPOTP PUMP INLET TEMPERATURE (R)
22. HPOTP PUMP DISCHARGE TEMP. (R)
23. HPFTP PUMP DISCHARGE TEMP. (R)
24. MFV DISCHARGE TEMPERATURE (R)
25. PB PUMP DISCHARGE TEMP. (R)
26. HPFTP PUMP INLET TEMPERATURE(R)
27. LPOTP TURBINE SPEED (RPM)
28. LPFTP TURBINE SPEED (RPM)
29. HPOT DISCHARGE TEMP (R)
30. HPFT DISCHARGE TEMP (R)
31. OPB OXIDIZER VALVE RESISTANCE
32. FPB OXIDIZER VALVE RESISTANCE
33. OXIDIZER PRESSURANT PRESSURE (PSIA)
34. FUEL PRESSURANT TEMPERATURE(R)
35. OXIDIZER PRESSURANT TEMPERATURE (R)
36. FUEL PRESSURANT TEMPERATURE (R)
37. LPOTP PUMP SUCTION SPECIFIC SPEED
38. LPFTP PUMP SUCTION SPECIFIC SPEED
39. HPOTP PUMP SUCTION SPECIFIC SPEED
40. HPFTP PUMP SUCTION SPECIFIC SPEED
41. MCC COOLANT DISCHARGE PRESSURE (PSIA)
42. MCC COOLANT DISCHARGE TEMPERATURE (R)
43. LPOTP TURBINE TORQUE (FT-LB)
44. LPFTP TURBINE TORQUE (FT-LB)
45. HPOTP TURBINE TORQUE (FT-LB)
46. HPFTP TURBINE TORQUE (FT-LB)
47. LPOTP TURBINE FLOWRATE, LBM/S
48. LPFTP TURBINE FLOWRATE, LBM/S
49. HPOTP TURBINE FLOWRATE, LBM/S
50. HPFTP TURBINE FLOWRATE, LBM/S
51. LPOTP TURBINE INLET PRESSURE, PSIA
52. LPFTP TURBINE INLET PRESSURE, PSIA
53. HPOTP TURBINE INLET PRESSURE, PSIA
54. HPFTP TURBINE INLET PRESSURE, PSIA
55. LPOTP TURBINE INLET TEMPERATURE, (R)
56. LPFTP TURBINE INLET TEMPERATURE, (R)
57. HPOTP TURBINE INLET TEMPERATURE, (R)
58. HPFTP TURBINE INLET TEMPERATURE, (R)
59. LPOTP TURBINE DISCHARGE PRESS., PSIA
60. LPFTP TURBINE DISCHARGE PRESS., PSIA
61. HPOTP TURBINE DISCHARGE PRESS., PSIA
62. HPFTP TURBINE DISCHARGE PRESS., PSIA
63. LPOTP POWER
64. LPFTP POWER
65. HPOTP POWER
66. HPFTP POWER
67. HOT GAS MANIFOLD FUEL SIDE INLET PRES
68. HOT GAS MANIFOLD OX SIDE INLET PRESS
69. OXIDIZER T/D DYNAMIC HD
70. OXIDIZER T/D FLOW VELOCITY
71. FUEL T/D DYNAMIC HEAD
72. FUEL T/D FLOW VELOCITY
73. HOT GAS MANIFOLD FUEL SIDE TEMP.
74. HOT GAS MANIFOLD OXIDIZER SIDE TEMP.
75. OPB POWER
76. FPB POWER
77. MAIN INJECTOR POWER
78. MANIFOLD PRESSURE OXIDIZER FPB OR OPB
79. MANIFOLD PRESSURE FUEL FPB OR OPB
80. P/B INLET TEMP OXIDIZER FPB, OPB
81. P/B INLET TEMP FUEL FPB, OPB
82. M/INJ DYN HD
83. M/INJ VELOCITY
84. OPB DYN HD
85. OPB VELOCITY
86. FPB DYN HD
87. FPB VELOCITY
88. BOOST PUMP DISCHARGE TEMP
89. HPOTPDD - HPOP DISC. DYN HD
90. HPOTPDD - HPOTP VEL. HD.
91. HPFPDD - HPFP DISCHG DYN HD
92. HPFPDD - HPFP VEL. HD.
93. BOOST PUMP DISCHG. DYN HD
94. BOOST PUMP DISCHG. VEL
95. HGM COOLANT PRESSURE FUEL & OXIDIZER
96. HGM COOLANT TEMP FUEL & OXIDIZER
97. ENGINE EXHAUST VELOCITY

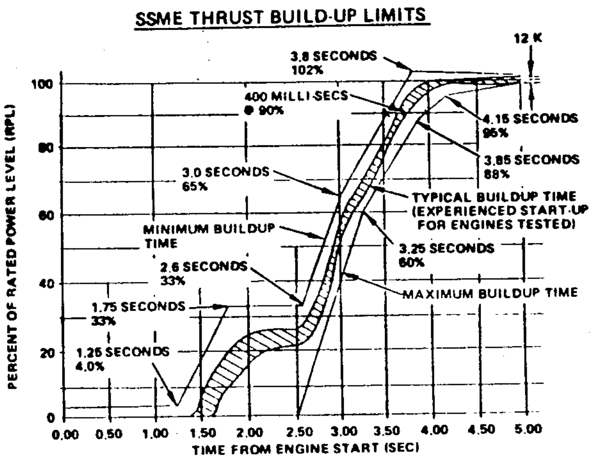
3.5 Transient Loads

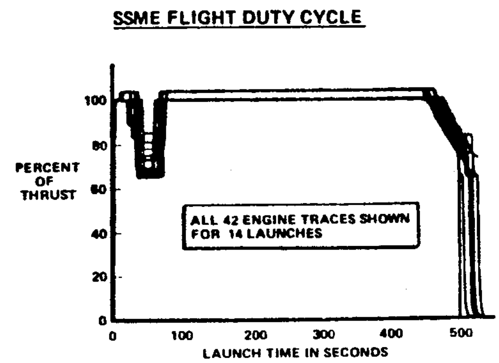
The engine duty cycle can be divided into two parts - transient and steady state or quasi-steady state. The transient portion requires inclusion of dynamic aspects of the system which considers engine operation parameters - flows, pressures, temperatures, etc. and control system parameters - valve sequencing, timing, etc. These are based on an engine transient model that is similar to the performance model that includes the addition of variables to analyze the time related aspects of the model and covers the total range of power level and flow regimes. The model is typically less exact and has simpler component representation than the performance model, but the differences are not large from a total magnitude standpoint of the key variables used in a load analysis.

The duty cycle conditions of several key variables are typically controlled by contractual requirements. Figure 5 shows how the SSME thrust buildup is contractually controlled as well as the overall thrust profile of the duty cycle. The basic transient analysis philosophy has been reported in previous annual reports. From an engine operation standpoint, a normalized set of transient variables are defined over the start and cutoff time period up to steady state operation. These conditions can be based on a specific engine. (SSME) or scaled proportional to a key variable such as a contractual power level requirement to evaluate a generic condition. Both mean and a distribution are included in the model. This basic philosophy has been used by Battelle in developing the probabilistic load model. This basic model includes surge effects, when based on detail analysis, but is not available from a generic point where less developed modeling information is available.

CONTRACTURAL REQUIREMENTS PARTIALLY CONTROL LOADS

- POWER LEVEL
  - TRANSIENT
  - STEADY STATE
- MIXTURE RATIO – OXIDIZER TO FUEL MASS FLOWRATE REQUIREMENTS AT PUMP INLETS
  - PRESSURES
  - TEMPERATURES





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87C-4-2833

Figure 5. SSME Thrust Buildup

These surges and other transient loads that are more randomly triggered and are not considered in the engine models can be better addressed by a set of time-phased, timeline of events, Figure 6. These events are either control system parameters, e.g., valve opening conditions, or analysis events known to occur in the transient operation, e.g., injector dome priming, fuel side oscillation. These events can be related to surges, large thermal transients, chugging, pops and sideloads so that the expert system can request the probabilistic model to spawn the "spike" type load within a reasonable time window.

The probabilistic transient model including spike loading is implementated in the ANLOAD code and partially in the expert system code. The generic transient duty cycle definition and appropriate timeline - operation parameters and parallel event timing rules have to be added to the expert system.

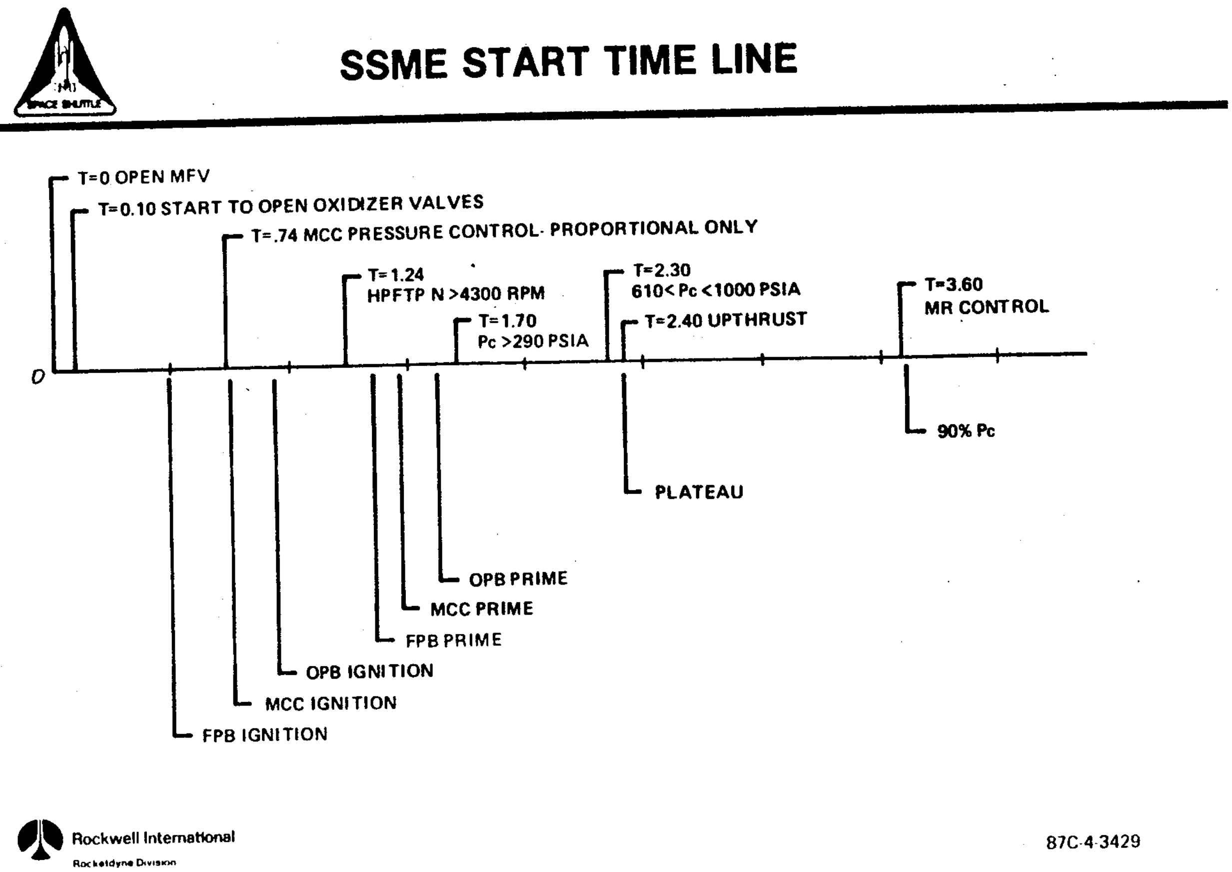

Figure 6. SSME Start Timeline

3.6 Generic Model for Chug Combustion Instabilities

A fresh look at the available background information has been made and a generic model partially developed. The model considers primarily injector elements, manifolds and upstream ducting effects on the flow in defining stability modes and frequencies at specific flow conditions, see Figure 6. Basic longitudinal chamber modes are also considered for defining when coupling of modes occur. This model covers the transient conditions as well as steady state operation. The model has been tested against a current engine problem (non-SSME'S) that has a demonstrated combustion instability. Other injectors - stable and unstable - will also be looked at as time permits. The methodology has potential usage for basic design and test analysis as well as the CLS work.

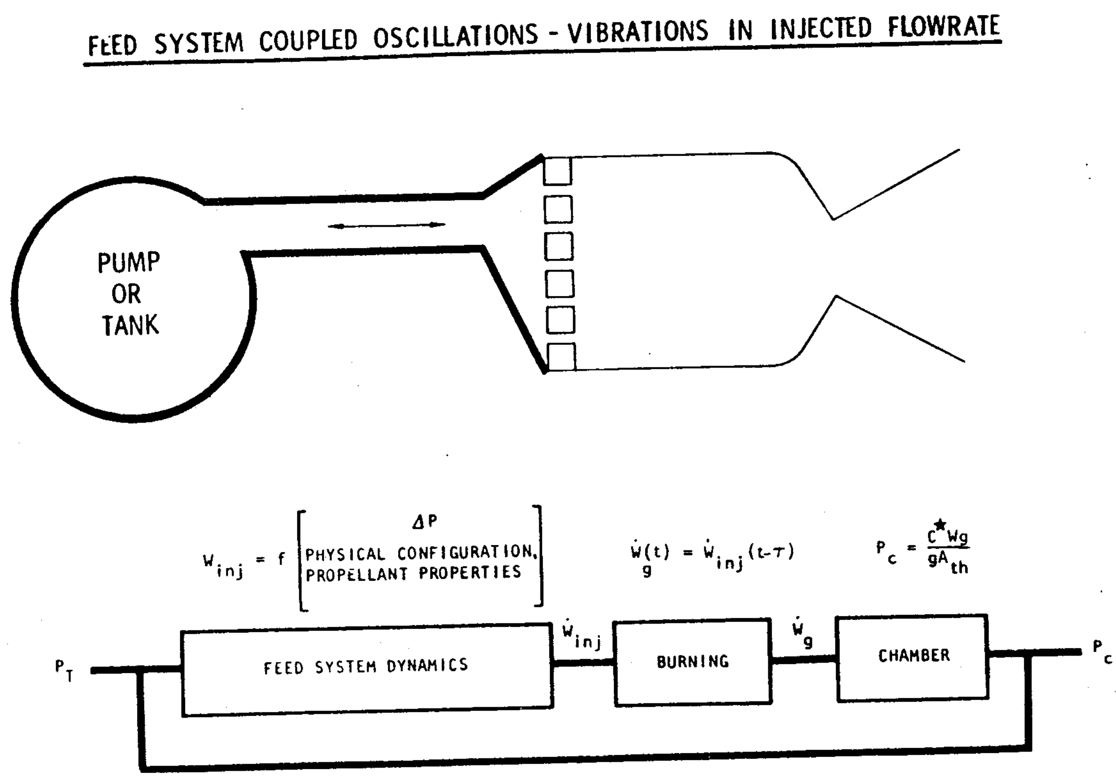

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Figure 7. Feed System Coupled Oscillations-Vibrations in Injected Flowrate

3.7 Thermal Loads

Baseline thermal models have been developed for three of the four components (hot gas manifold, HPFTP second stage turbine blade, and main injector LOX post). The fourth component, the HPOTP discharge duct, operates at constant temperature and does not require a model. The other three component models are based on the methodology discussed below. The methodology evolved with each component analysis. Also, the order of analysis was chosen from the simplest thermal model, the transfer duct steady state model, to the most complex, the LOX post transient model. The models are consistent with the potential usage in PSAM. The turbine blade thermal model has been successfully used for that purpose.

The challenge was to come up with a simplified model methodology that accounts for the primary variables that affect the overall temperature distribution without requiring a complete probabilistic heat transfer model. The essence of the evolved technique is as follows:

1. Reference thermal states (steady state and transients at specific time slices) of the component are used as baseline temperature distributions.

2. The component is divided into regions of primary influence of a load variable or variables. The method of division is to use specific reference isotherms (in the case of the turbine blade) or physical dimensions (in the case of the LOX post).

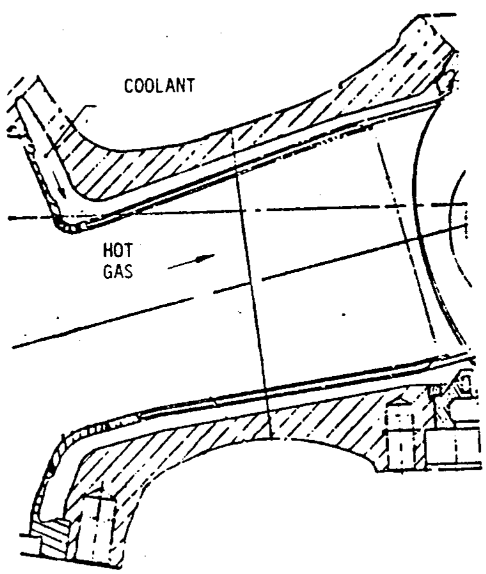
3. Each region is characterized by the maximum and minimum temperature of that region. When using isotherms to partition a component, each isotherm will correspond to either the maximum or minimum temperature of the region that it bounds.

4. Scaling relationships between the primary independent variables (hot gas and coolant temperatures, flowrates, geometry influence parameters, etc.) and the maximum and minimum temperatures for each region are derived. These scaling relationships are put in the form of influence coefficients in order to be compatible with the probabilistic load model and expert system.

5. Using the scaling relationships, the maximum and minimum temperature for each region can be determined for any set of conditions. Using the reference temperature distribution, the temperatures at other locations within the region are then calculated by scaling linearly between the newly derived maximum and minimum temperatures. This procedure insures compatibility of temperatures throughout the model (no discontinuities).

The accuracy of the solution is a function of the complexity of the thermal loading and the number of regions. The first model developed, the transfer duct, Figure 8, considered only steady state conditions, had only one region, and used only the hot gas and coolant temperatures (the two most significant boundary conditions) as the independent variables. It still achieved reasonable results when validated against a detailed heat transfer model. The accuracy would easily be improved by dividing the model into thermal regions where quite different heat transfer conditions occur.

FIRST COMPONENT - HGM FUEL CENTER TRANSFER TUBE



- 2 INDEPENDENT VARIABLES
  - HOT GAS TEMPERATURE
  - COOLANT TEMPERATURE
- TWO-DIMENSIONAL
- STEADY STATE
- 1 REGION
- LINEAR INFLUENCE COEFFICIENTS
- PROBABILITY DISTRIBUTIONS (NORMAL)
  - HOT GAS: μ = 1558°R COV = 0.05
  - COOLANT: μ = 495°R COV = 0.05

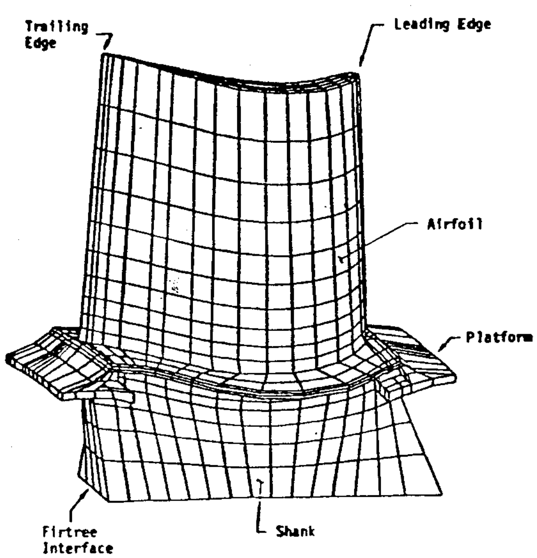
Figure 8. Transfer Duct Thermal Model

The turbine blade model, Figure 9, also considered only steady state conditions but was divided into three regions and addressed the problem of significant local heat transfer changes by defining local geometric variables.

The LOX post model, Figure 10, adds in the complexity of both transient and steady state operation and additional boundary heat transfer variations. The detail model development was furnished in the monthly reports and will be part of the code manuals.

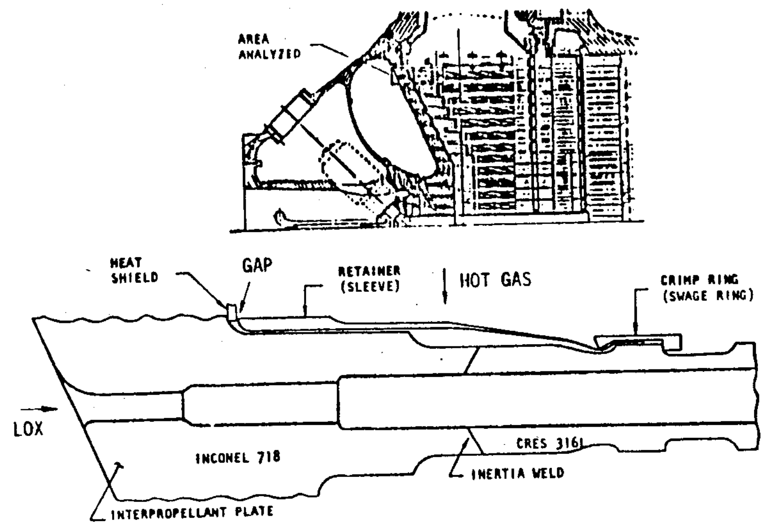
The implementation of the models in the expert system is such that a user can interface at the detail temperature level at nodes or elements or at the major component level, such as the turbine boundary.

2ND COMPONENT - HPFTP SECOND STAGE TURBINE BLADE



- 5 INDEPENDENT VARIABLES
  - TURBINE INLET TEMPERATURE
  - TURBINE DISCHARGE TEMPERATURE
  - PUMP DISCHARGE TEMPERATURE
  - GEOMETRIC INFLUENCE ON COOLANT FLOWRATE
  - GEOMETRIC INFLUENCE ON HOT GAS LEAKAGE
- 3-DIMENSIONAL
- STEADY STATE
- 3 REGIONS (USE REF. ISOTHERMS)
- LINEAR INFLUENCE COEFFICIENTS
- ESTIMATE RANGE FOR GEOMETRIC INFLUENCE PARAMETERS
- PROBABILITY DISTRIBUTIONS (NORMAL)
  - T_{IN} : μ = 2012°R, σ = 35
  - T_{OUT} : μ = 1831°R, σ = 32
  - T_{PUMP} : μ = 100°R, σ = 2
  - G_H : μ = 1.0, σ = .06
  - G_C : μ = 1.0, σ = .145

Figure 9. Turbine Blade Thermal Model



ANALYSIS CONDITIONS

- 8 INDEPENDENT VARIABLES
  - HOT GAS TEMPERATURE
  - COOLANT TEMPERATURE
  - HOT GAS FLOWRATE
  - COOLANT FLOWRATE
  - MIXTURE RATIO
  - HEAT SHIELD - RETAINER GAP
  - HOT GAS COEFFICIENT UNCERTAINTY
  - COOLANT COEFFICIENT UNCERTAINTY
- 2-DIMENSIONAL
- STEADY STATE AND TRANSIENT
- 3 REGIONS
- QUADRATIC INFLUENCE COEFFICIENTS
- PROBABILITY DISTRIBUTIONS DEFINED FOR INDEPENDENT PARAMETERS
  - GAP: $\mu = 0.002''$ (EXPONENTIAL)
  - H_G FACTOR: $\mu = 1$, $\sigma = 0.1$ (NORMAL)
  - H_C FACTOR: $\mu = 1$, $\sigma = 0.08$ (NORMAL)

Figure 10. Lox Post Thermal Model

3.8 Mechanical Vibration

Vibration loads are a major consideration on rocket engines - especially reusable long life high performance ones like the SSME. From an engine standpoint there are primarily three sources of these loads - the combustion process, fluid flow/internal acoustics loads and rotating machinery loads. The mechanical vibration that is used for environments on engine models or components are responses to these sources, not direct measurements of the forcing function. The flow dynamic pressure load component considered separately from mechanical vibration is a direct measure of one of these sources. As discussed in previous project reports, historically vibration loads have been scaled for new engines and differences in power level by Barrett's criteria combined from developed engines with judgments on how a component on a previous engine is similar to the new engine.

In addition, few measurements and basic data are available from earlier engines to make detail comparative studies with the SSME engine where extensive measurements and environments are defined. The Barrett and SSME approach is to define vibration maximum envelopes that furnish a conservative design for a deterministic analysis approach. This has been usable for an initial design criteria, but is costly from a hardware usage standpoint where the decision to retire expensive hardware needs to be made on an actual environment basis. The CLS approach uses both a less conservative maximum envelope and a direct measure of average response with a distribution. This is more directly usable for basic design and as built life definition.

Figure 11 shows where some of the standard engine measurements including vibration monitoring accelerometers are located on the SSME engine. For defining the engine environments data was collected on all major elements of the engine and zones defined for their use. A study of these zonal environment levels readily show that Barrett's technique of relating everything to engine thrust, mass and exit velocity is too crude for an accurate assessment. A more appropriate generic approach is to relate the vibration levels to each individual energy generating/loss component and combine their effects in an appropriate model. The primary energy generating components, are combustors and turbopumps - e.g. 3 combustors on the SSME and four turbopumps. The approach used on the CLS work is described in last years annual report. Figure 12 depicts the essence of how the steady state vibration response is approached.

The random and sinusoidal environments are separated since they have significantly different model variables. The random is approached as a segmented response level vs. frequency that has a mean value and distribution in level and frequency. The sinusoidal response has a frequency dependent on turbopump speed and its variation with a mean response level and distribution. Coupling between sinusoidal frequencies is accounted for. The vibration models are simplified in the baseline code and will be improved during the option phase of the program. The transient portion of the mechanical vibration load - pops and sideloads are covered as separate loads since they must be handled differently in the probabilistic model and expert system code.

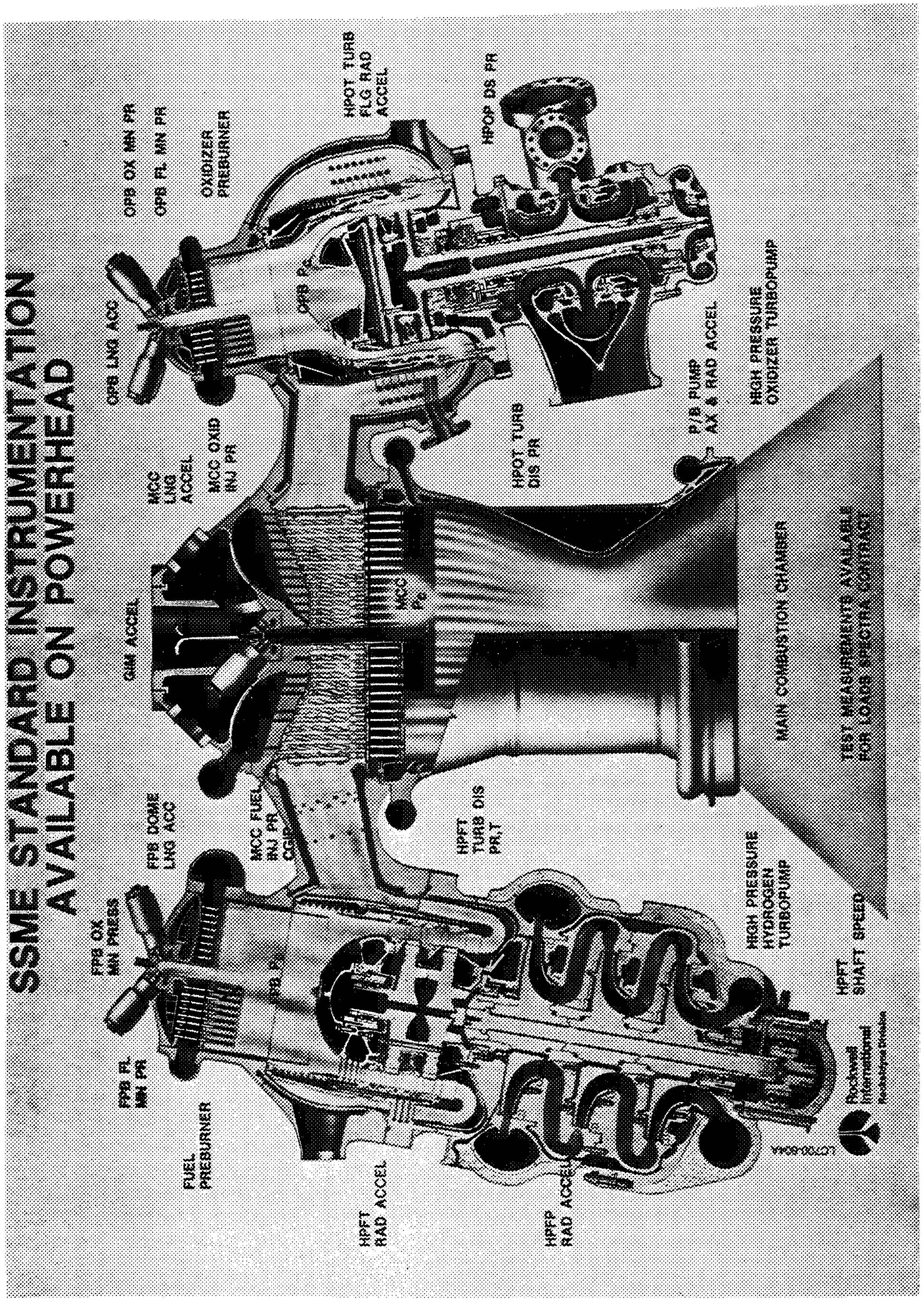


Figure 11. SSME Standard Instrumentation

MECHANICAL VIBRATION

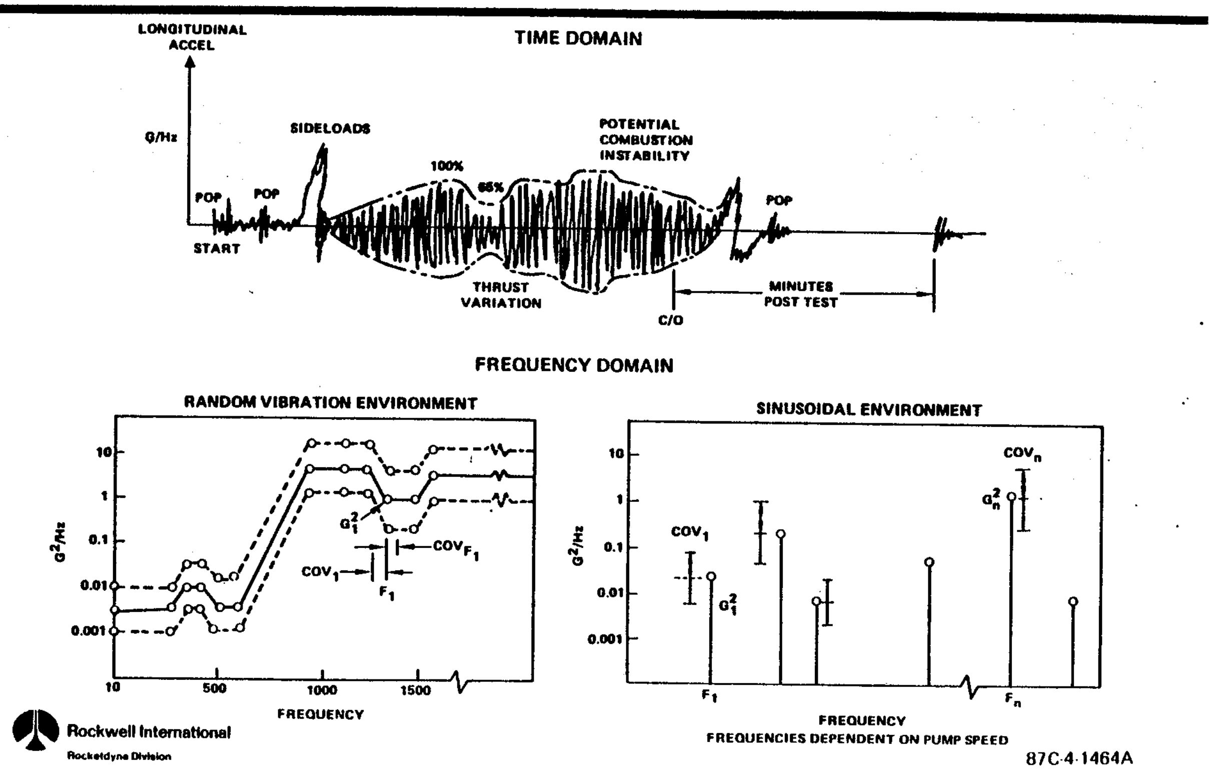


Figure 12. Mechanical Vibration Overview

4.0 TRANSFER DUCT MODEL

4.1 General

Hot gas transfer ducts in rocket engines transfer hot turbulent flow between major components of a engine. For example the SSME transfer ducts contain the turbine exhaust flows from the high pressure turbopumps and exhaust their flow into the main injector hot gas cavity. In this case the ducts are thin walled sheet metal that are pressure balanced with an exterior coolant flow. The pressure containing shell sees the coolant flow and temperature. Alternate configuration might not have the liner and the inner surface of the pressure containment vessel would experience the exhaust flow. A transfer duct may also have a dual shell with an inner scrub liner that protects the primary duct from a portion of the thermal loading (e.g. SSME Figure 7).

Figure 13 depicts a schematic of a transfer duct and a portion of the loading. The thermal load (T_i), and mechanical vibration are developed in separate sections, but their engine parameters will be part of this discussion. The static pressure - hot gas exhaust pressure (p_e) and the coolant pressure (P_c) are essentially constant along the duct and are determined directly from the 1-D pressures from the engine model results. Both steady state or slowly varying power levels and transient results can be obtained in this manner. The vibration and shock loads are base excited vibrations through the ends of the duct that are dependent on the power level of the injectors and turbopumps. The hot gas and coolant temperatures are used in defining the transfer duct thermal environment.

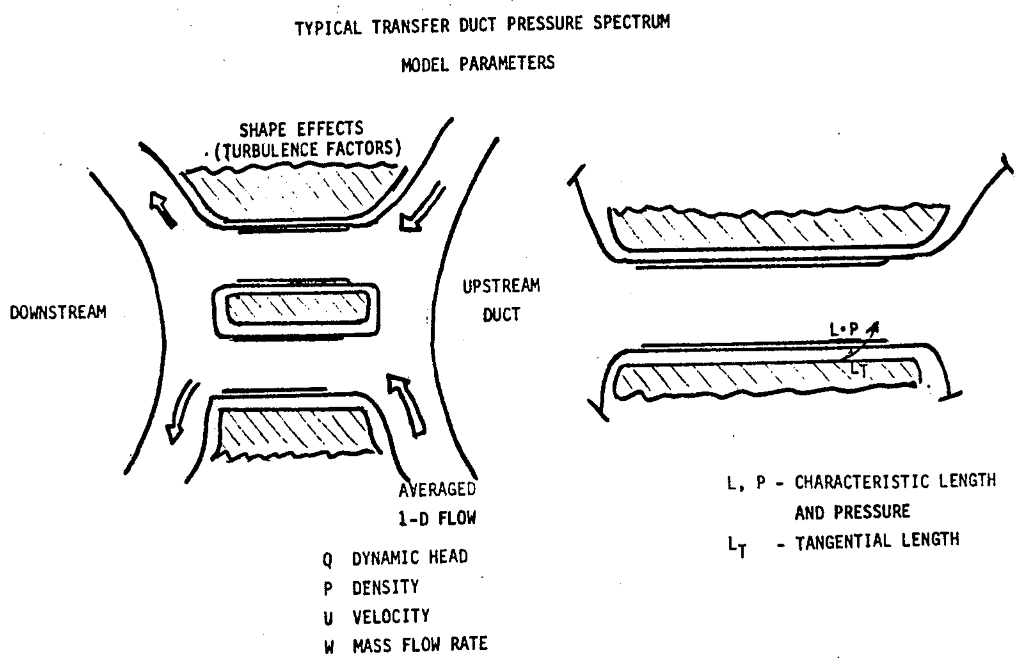


Figure 13. Typical Transfer Duct Flow Load Parameters

SSME TRANSFER DUCT ENGINE MODEL PARAMETERS

Fuel Side (HPFTP Parameters)	Oxidizer Side HPOTP Parameters)
Turbine Discharge	Turbine Discharge
Pe Pressure (PSI)	Pe Pressure (PSI)
Te Temperature (°R)	Te Temperature (°R)
Q_e HGM Dynamic Head (PSI)	Q_e HGM Dynamic Head (PSI)
Uc HGM Flow Velocity (ft/sec)	Ue HGM Flow Velocity (ft/s)
Pc LPFT Pressure (PSI)	w HPOT Flowrate (lbm/sec)
w HPFT Flowrate (lbm/s&c)	Pe LPFT Pressure (PSI)

Table 4. Transfer Duct Configuration Parameters

Geometry	3 Duct Fuel	HGM LOX	SSME 2 Duct Fuel	SSME HGM LOX	Generic P/BR Liner
Number of Ducts	3	2	2	2	1
End Fixity					
.Inlet Fixed	X	X	X	X	X
Free	-		-	-	-
.Outlet Fixed	-	-	-	-	-
Free	-	-	-	-	X
.Wall Configuration					
.Single - Pressure/Thermal					
.Double	X	X	X	X	X
.Inner Shell - Thermal Barrier	X				
.Outer Shell - Structural					
.Coolant					
.Scrub Liner	X	X	X	X	0
.Inlet					
.Transverse Flow	90	90	90	90	
.Contour					
.Sharp	X	X	-	X	
.Smooth	-	-	-	-	
.Optimum	-	-	X	-	
.Upstream Turbulence					
.PRMS	Low	Low	Low	Low	Low
.Outlet					
.Transverse Flow	90	90	90	90	
.Contour					
.Sharp	X	X	X	X	
.Smooth	-	-	-	-	
.Optimum	-	-	-	-	
.Duct Geometric Parameters					
D	4.1 to 5.3	3.95	2.9 to 11 OVAL	3.95	
L	6.75, 9 to 19	7 to 9	7.1 to 5.96	7 to 9	

Table 4 summarizes the important geometric parameters for transfer ducts and the parameters used from the SSME engine model that are used in the load calculations.

4.2 Transfer Duct Dynamic Pressure Loading

The objective of this task is to develop a predictive capability for the pressure spectrum and correlation lengths for flows through transfer ducts at many different locations and geometries. The pressure spectrum defines the pressure energy density as a function of frequency while the correlation length defines a typical length scale over which the pressure loading is being imparted. These two parameters are important in determining whether a particular component, subjected to this loading, will structurally survive this environment.

This methodology will be part of the CLS code. The predictive capability needs to be a function of standard 1-D flow relationships available from analysis like engine models and geometric parameters such as: apportioned flows, dynamic head, flow velocity, areas, diameters, duct lengths, entrance and exist conditions, etc. The flow parameters will be a function of the duty cycle of the engine. Figure 14 outlines the important features of the methodology. Geometric data is required to define flow conditions in a particular duct.

In an engine model, the collective flow through parallel ducts are typically combined into one area and flow condition. For an individual transfer duct, these averaged parameters have to be resolved to the individual divided flow conditions area and duct diameter. For instance on the SSME HGM the transfer duct flow is divided into 2 parallel ducts on the oxidizer side and 3 parallel ducts on the fuel side. The entrance and exit geometric conditions must also be defined so that the amount of separation at the inlet of the duct can be defined, see Table 5.

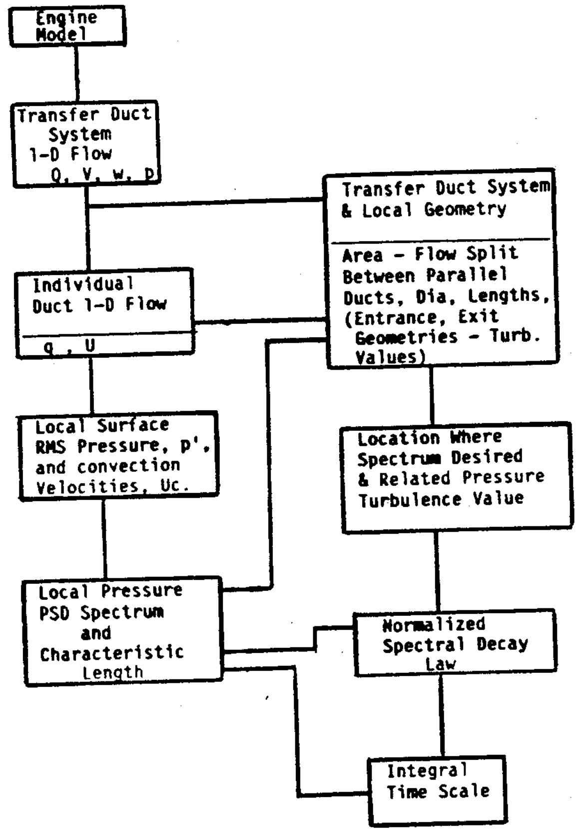


Figure 14. Pressure Spectrum Flow Chart

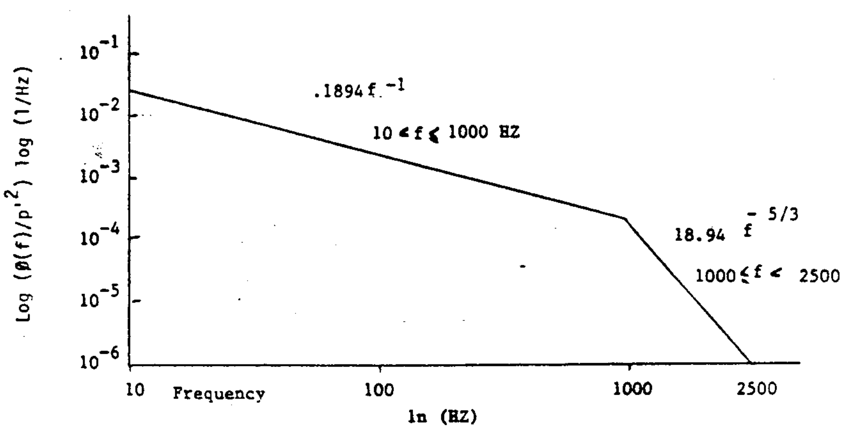


Figure 15. Transfer Duct Normalized Dynamic Pressure Frequency Distribution

PRESSURE TURBULENCE VALUES, P'/Q, FOR TRANSFER DUCTS

	TOP MEAN COV	BOTTOM MEAN COV
OPTIMALLY DESIGNED INLET WITH TRANSVERSE FLOW AT INLET	.15* .10	.15* .10
SHARP TRANSITION WITH TRANSVERSE FLOW AT INLET	.15* .10	.30* .10
CENTER OF "LONG" DUCT - L<2	.05 .50	.05 .50
ADDITIVE EFFECT OF HIGH UPSTREAM PRESSURE TURBULENCE	$2\left(\frac{u'}{U}\right)^2$ .5	$2\left(\frac{u'}{U}\right)^2$ .5
OPTIMALLY DESIGNED INLET - AXIAL INLET FLOW	0.01, 0.2	0.01, 0.2
SHARP TRANSITION INLET AXIAL INLET FLOW	0.15, 0.50	0.15, 0.50

*THESE VALUES, MEAN AND COEFFICIENT OF VARIATION, ARE BASED ON HGM COLD FLOW TESTS, THE OTHER VALUES ARE BASED ON EXPERT OPINION AND RELATED DATA IN THE LITERATURE.

Table 5. Transfer Duct Pressure Turbulence Values

The 1-D dynamic head and pressure turbulence intensity value based on local conditions at the point of interest are used to calculate the rms pressure (p') at the location on the transfer duct wall in question.

The normalized spectral decay law developed in this study (Figure 15) is then used with p' to define the pressure spectrum at the location in question. The correlation length is then calculated from the 1-D convection velocity and the integral time scale parameter (discussed below).

The pressure turbulence intensity factors, spectral decay law and integral time scale are based on data analysis and correlation from SSME cold flow tests of a simulated HGM where the transfer duct was instrumented to obtain local pressure fluctuations.

The approach used to calculate the correlation length for use with the pressure spectrum is summarized in Table 7. The correlation length relates the integrated effect on one local point from adjacent points. The correlation coefficient that relates the effects of this combined pressure is related then to the frequency spectrum, integrated time scale and the convection velocities of large scale eddies. Using these variables specifically for each duct configuration, a numerical evaluation of the correlation length is determined using Table 6 over the appropriate integration limits (0 to D/U).

Thus, the correlation length scales determined in this manner are 3.57 and 2.50 inches for the fuel and oxidizer side, respectively, values which are close to the radius of the ducts.

Table 6. Correlations Coefficient as a Function of the Time Difference

T (SECOND)	$R_c(T)$
.00000	1.00000
.00010	.92926
.00020	.78222
.00030	.67049
.00040	.62420
.00050	.59526
.00060	.55409
.00070	.52038
.00080	.50778
.00090	.49701
.00100	.47407
.00110	.45203
.00120	.44140
.00130	.43141
.00140	.41358
.00150	.39742
.00160	.39037
.00170	.38399
.00180	.37138
.00190	.35954
.00200	.26968

Table 7. Correlation Length Method Development Outline

- L - LENGTH ALONG FLOW DIRECTION FLUCTUATIONS ACT
- $L = \int_0^\infty R(X)\, DX$ — R - CORRELATION COEFFICIENT BTWN POINTS x APART
- FOR A STATIONARY RANDOM FLUCTUATION

  $R(\tau) = \int_0^\infty \Phi(\omega) \cos \omega\tau \, D\omega$ — TIME CORRELATION

  $\Phi(\omega) = \frac{2}{\pi} \int_0^\infty R(\tau) \cos \omega\tau \, D\tau$ — FREQUENCY SPECTRUM

- $T_X = \int_0^\infty R(\tau)\, D\tau$ — INTEGRAL TIME SCALE
- $L_X = U_C\, T_X$ — U_C CONVECTION VELOCITY OF LARGE SCALE EDDIES
- $U_C = .6\, U_\infty$ — U FREE STREAM 1-D VELOCITY
- $R_C(\tau) = \frac{1}{P^2} \left[\int_{10}^{1000} .1894\, f^{-1} \cos \omega\tau D\omega + \int_{1000}^{2500} 18.94\, f^{-5/3} \cos \omega\tau D\omega \right]$

  $0 < \tau < \frac{D}{U}$

- $T_X = \int_0^{D/U} R_C(\tau)\, D\tau$ - EVALUATED NUMERICALLY
- L (FUEL DUCT) = 3.57 IN.
- L (OXID DUCT) = 2.50 IN.

5.0 PROBABILISTIC MODELING

5.1 Introduction

This section reports on the progress and development of the probabilistic load model for generic space propulsion engines. This effort is part of the program being conducted by Rocketdyne and Battelle Columbus Division for NASA Lewis Research Center to develop an expert system to predict the composite loads in a generic space propulsion engine. The ultimate goal of the program, to be able to address generic engines that may include different mission profiles or incorporate design changes, requires that a robust and general probabilistic approach be adopted for inclusion in the expert system model. During the first year of the program, a survey was conducted to select these models and the initial programming, debugging and shake-down analyses were performed. The second year of the program was oriented towards building the probabilistic methodology, developing a data base that can be used by both the probabilistic methodology, as well as the expert system, including different functional forms for the load description, model verification and validation, and the generalization of the computer program system. The third year of the program has focused primarily on the refinement of the current methodology, the improvement of the transient load model, the incorporation of the periodic load model, the verification of the probabilistic methodology, and documentation.

The probabilistic model includes three probabilistic methods: (1) a moment propagation method which assumes that all of the load variables and engine parameters are normally distributed, (2) a discrete probability method (RASCAL), and (3) Monte Carlo. The moment propagation method, referred to as the Quick

Look Model (QLM) provides a fast, efficient method for determining the composite load distribution, if the basic variables' distributions are not severely skewed. The RASCAL method is a discrete method capable of handling standard distributional forms, e.g. normal, lognormal, Weibull, and so on, non-standard forms such as bi-modal, and provides a range of levels for accuracy. This method can also be used to perform importance sampling which can be used to examine regions of concern for the composite load even though such values would be unexpected during nominal engine operation. Finally, Monte Carlo analysis is available so that classical confidence limits can be obtained to assess the accuracy of the composite load prediction.

All phases of the mission history profile are addressable by the probabilistic load model. Currently, each mission profile is divided into phases that are defined as transient, quasi-steady, or steady state phases. The transient phase is characterized by rapid changes in the amplitude of the individual loads and engine parameters. The rapid changes allow the program to ignore small oscillations about the much larger nominal load fluctuations. The uncertainty in the load is caused by the variability in the peak load value and its time of occurrence. The quasi-steady phase is that portion of the mission where the nominal value of the load is slowly changing and thus, can be approximated by "staircase" type quasi-steady state steps. The steady state region is where the nominal values of all of the individual and composite loads are approximately constant. Unlike the transient phase, both the quasi-steady and steady state phase do have fluctuations superimposed upon the nominal behavior. Additionally, each of these phases can have "spike" values superimposed which represent the occurrence of rare events.

The linking of these different mission phases has been completed. It has been demonstrated that for the cases where data have been available that a continuous, nominal behavior is achieved. In addition, the predicted variability and the measured variability are well within acceptable limits for the cases tested to date. Therefore, the extension of the model has proceeded to engines and mission definitions for which little or no data exist.

Documentation of the code has continued throughout the program. Periodically, new versions of the program are sent to Rocketdyne for incorporation into the expert code system. The computer code to date has addressed the loads that are dependent on the overall engine performance and that are directly relatable to the engine model and duty cycle. The latest phase of the composite load model development addressed the remaining loads: i.e., the vibration environment, shocks, and "pops" loads.

This report is organized to provide a summary of the work completed during the third year of the program. The complete users' manual, theoretical descriptions, and code installation will be performed early in 1988 when the final report for the base years of the composite loads program is presented to NASA. This report focuses on three areas primarily: (1) periodic (vibration) loads, (2) transient loads, and (3) improvements to the probabilistic methodology. Each topic is discussed in more detail in the following pages.

5.2 Transient Load Model

5.2.1 Introduction

The transient load model is provided to predict individual and composite load results during the (physical) transient portion of the engine mission history profile. Usually, during these phases significant departures from nominal behavior occur due to the non-equilibrium operation of the engine. For example, during the engine ignition, the temperature in the transfer ducts, turbines and LOX posts will change rapidly in what are referred to in this document as spike type events. A generic methodology has been developed to handle these types of events.

The previously developed transient load model was examined and found to not be of a general enough nature for generic space propulsion applications. Several modifications were recommended by Rocketdyne to provide a wider scope for the transient model. These modifications were suggested to incorporate a more generic capability in the model. The most significant changes were in the arrival of the spike loads. Previously, each spike load had to have its own mission phase assigned to it, with only the peak amplitude and the time of occurrence of the peak being random. Previously, only three types of mission phases were defined: transient, quasi-steady, and steady state. When the transient mission phase is required to be further sub-divided then, in reality, there are more than three mission phases. To correct this situation a new transient model is now available, and is discussed below.

First, the previous version of the model has been retained in the program since it is still useful, although not for as wide a range of scenarios as the updated version. This model is still identified as mission phase 1 in the input.

The new model is identified as mission phase 4 or 5 in the input. Mission phase 4 implies that the number of randomly occurring spikes obeys a Poisson arrival rate model. Mission phase 5 implies that the random spikes occur uniformly during the mission phase. Both models are available for the following reason. In a Poisson model, if the mean arrival rate is N events during the mission phase, then during the simulation there will be instances in which many more than N events occur. In many cases this is physically unrealistic. Therefore, a uniform model is also provided, since the user can then be insured that there is an upper bound for the number of spike type events which occur.

The second problem one encounters in developing this more generic model is that there are some events which must always occur, due to the physics of the engine, while subsequent events are randomly occurring. For example, there is always a temperature spike which occurs due to the engine ignition, but subsequently, there are one or two spikes which can occur. Therefore, a third type of model is available which requires fixed spikes to always occur.

While the number of spikes which occur may be random, there may be a time dependency, that is, given that the spike does occur, it is always within a specified time range. This capability is also included in the model.

The following paragraphs provide a more detailed explanation of the transient model operation. After this discussion, an example calculation is presented and discussed.

5.2.2 Transient Model: Determination of Number Of Spike Events

For all of these discussions, it will be assumed that the current mission phase, denoted as IMP, for load variable IR has already been determined to be of type 4 (Poisson model) or type 5 (Uniform model). These parameters are input as MP(IR,IMP) and are discussed in the user manual input description in more detail. The operation of the model for the quasi-steady and steady state type of mission phases is unaffected by these new changes.

The first step in the load model calculation is the determination of the number of the spike values seen during the mission phase. To calculate this number, three options are available to the user: (1) a Poisson arrival rate model, (2) a Uniform arrival rate model, and (3) a fixed time of arrival model. The Poisson arrival rate model is obtained by inputting MP(IR,IMP) equal to 4, while the uniform model is obtained with MP(IR,IMP) equal to 5. The definition of the subsequent inputs changes depending upon the value of the MP(IR,IMP).

The parameter needed as input for the Poisson arrival model is the mean arrival rate, called RAMDA(IR,IMP) in the program. This is equal to the mean number of spike events per mission phase time period. Thus, if there are 3 spike events, on the average for mission phase IMP and the phase is 5 seconds long, then RAMDA(IR,IMP) is equal to 0.6 (3 events/5 seconds).

The Poisson model does not have an upper bound on the number of events which can occur. For example the values given in the previous paragraph where the mean arrival rate is 3 there is approximately a 3.4% probability that there will be 7 or more events occurring in the 5 second interval. Since this can lead to physically unrealistic scenarios and mission profiles, an option for a two-sided distribution was believed to be necessary. For some load variables there will never be more that N events during the mission phase, and zero will always be a lower bound (although, it may not be the maximum lower bound). A uniform distribution is included to provide both an upper and a lower bound to the calculations. When MP(IR,IMP) is equal to 5 the uniform distribution is chosen. For this case RAMDA(IR,IMP) is equal to N+1, i.e. the maximum number of events which can occur plus one.

Finally, there should be a method for handling spike events which always occur but have some variability about either the nominal spike amplitude or the time of occurrence. This is input as NFIX(IR,IMP) greater than zero.

These are the only parameters which are needed to determine the number of spike events which occur during the transient mission phase. The next step is to determine when the event occurs.

5.2.3 Transient Model: Determination of Timing Of Spike Events

The timing of the spike events must rely on basic information about the mission phase definition that defines the amplitudes and timing of large excursions from nominal load levels. The previous transient model assumed that the spike event began and ended with the beginning and ending of the mission phase definition. This implies that the spike width is equivalent to the mission phase length. The new model allows for multiple peaks within the transient mission phase. However, this implies that the information about the spike width is lost. There are several options for dealing with the replacement of this information, but the one chosen, for this model development, is to input the nominal spike width and leave it fixed throughout the current mission phase. If the spike width changes dramatically from peak to peak then two approaches may be considered. The simplest is to divide the current mission transient phase into multiple mission phases in which the spike width can be considered constant. The other option is to make the spike width a random variable. This option requires information more detailed than the approximate nature of the model warrants. Therefore, the second option is not contained in the current version of ANLOAD. It can be added later if new data or information indicates that this is the better method.

The information on the spike width is input in the array denoted WIDTH(IR,IMP). The width of the spike is then constant for this mission phase time period, which is defined by the start time, STIME(IR,IMP), and the end time, ETIME(IR,IMP).

The start of the spike transient event is obtained in two different ways depending on the type of model used for the transient load modeling. For the Uniform model the spike transient can occur with equal probability in the mission phase time interval defined by ETIME(IR,IMP)-STIME(IR,IMP). For the Poisson model the start of the spike transient is given by a Poisson distribution with the mean time of occurrence input in the array TIMEJ(IR,IMP). This model will cause the spike values to be more likely to occur earlier in the mission phase than they are later in the mission phase. This is intuitively correct since one expects less of a departure from the nominal engine conditions as the mission phase is leaving the transient regime and approaching a quasi-steady or steady state operating condition.

5.2.4 Multiple Peaks In The Mission Phase

The previous description relates how the initial spike transient peak is placed in the mission phase time interval. Because there is some probability that more than one peak can occur one must decide if the peaks can overlap or if there is some time delay before the next spike transient value can occur. This is done by inputting the number of spike widths which must pass before the next peak can occur, which is denoted IDLAY in the ANLOAD program. If IDLAY is zero then peaks can overlap. This will cause a "masking" of peaks so that multiple peaks may actually appear as single peaks. This can lead to a reduction in the calculated variance.

The amplitude of the peak values is calculated after the timing of the peak occurs. This is done to reduce the array storage requirements in the program. Since the peak amplitudes are calculated at each time interval there is no need to store their values and the calculations proceed by calculating the first four moments of the load amplitudes. These moments are then sent to the distribution fitting subroutine and the best fit distribution is used to summarize the results on the output file.

The flowchart for this model is contained in Figure 16.

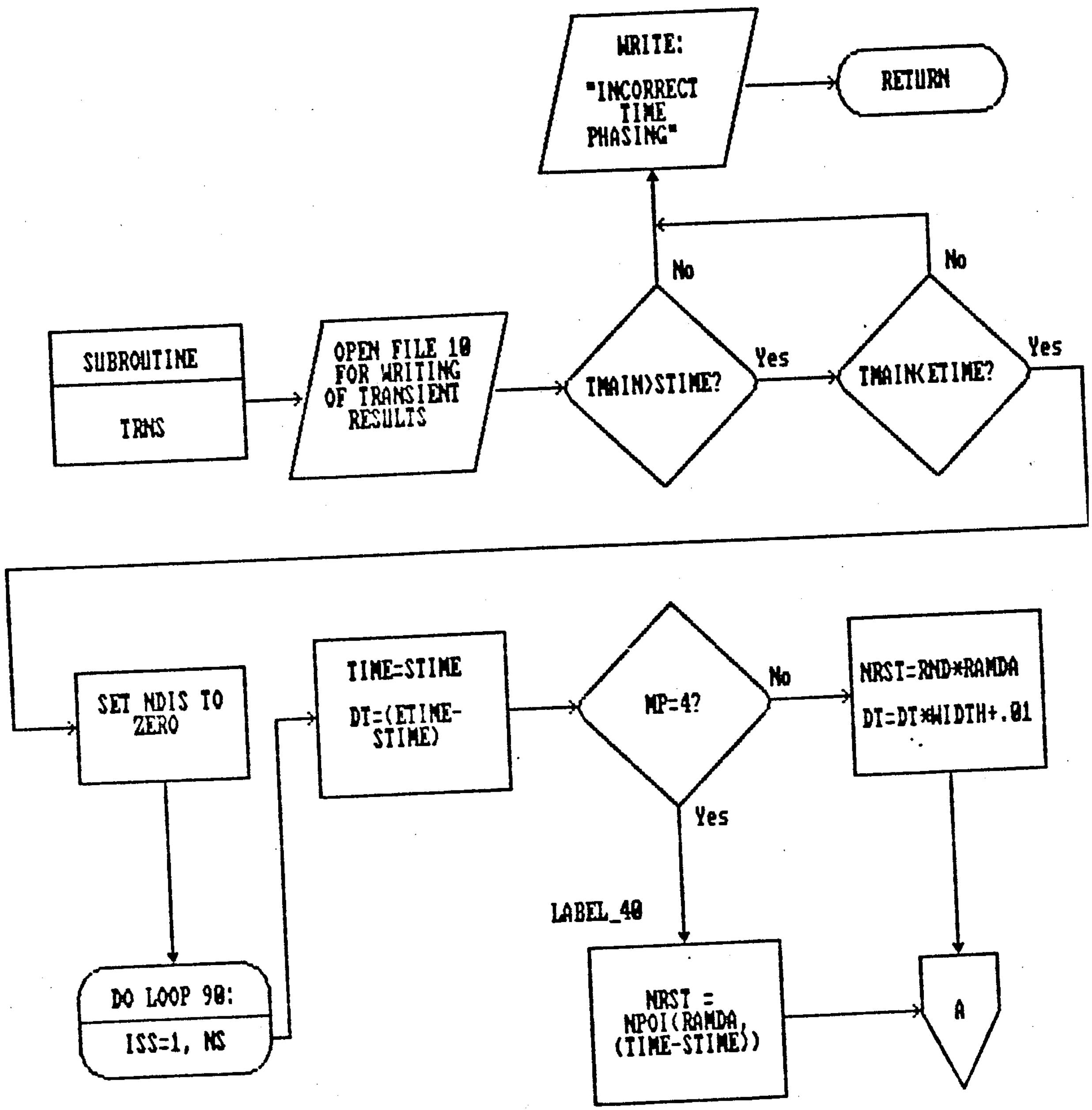


Figure 16. Transient Model Flowchart

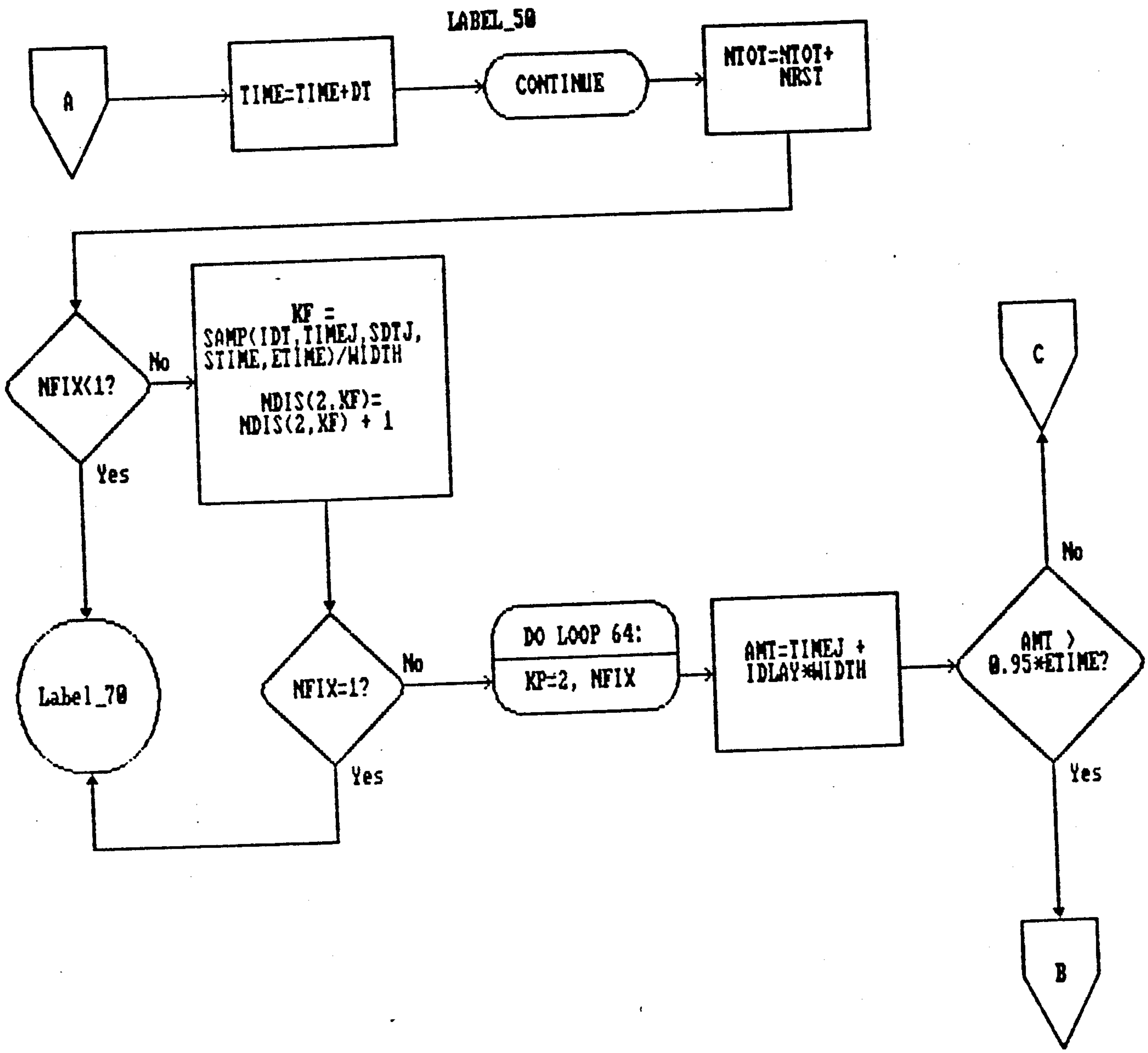


Figure 16. Transient Model Flowchart (continued)

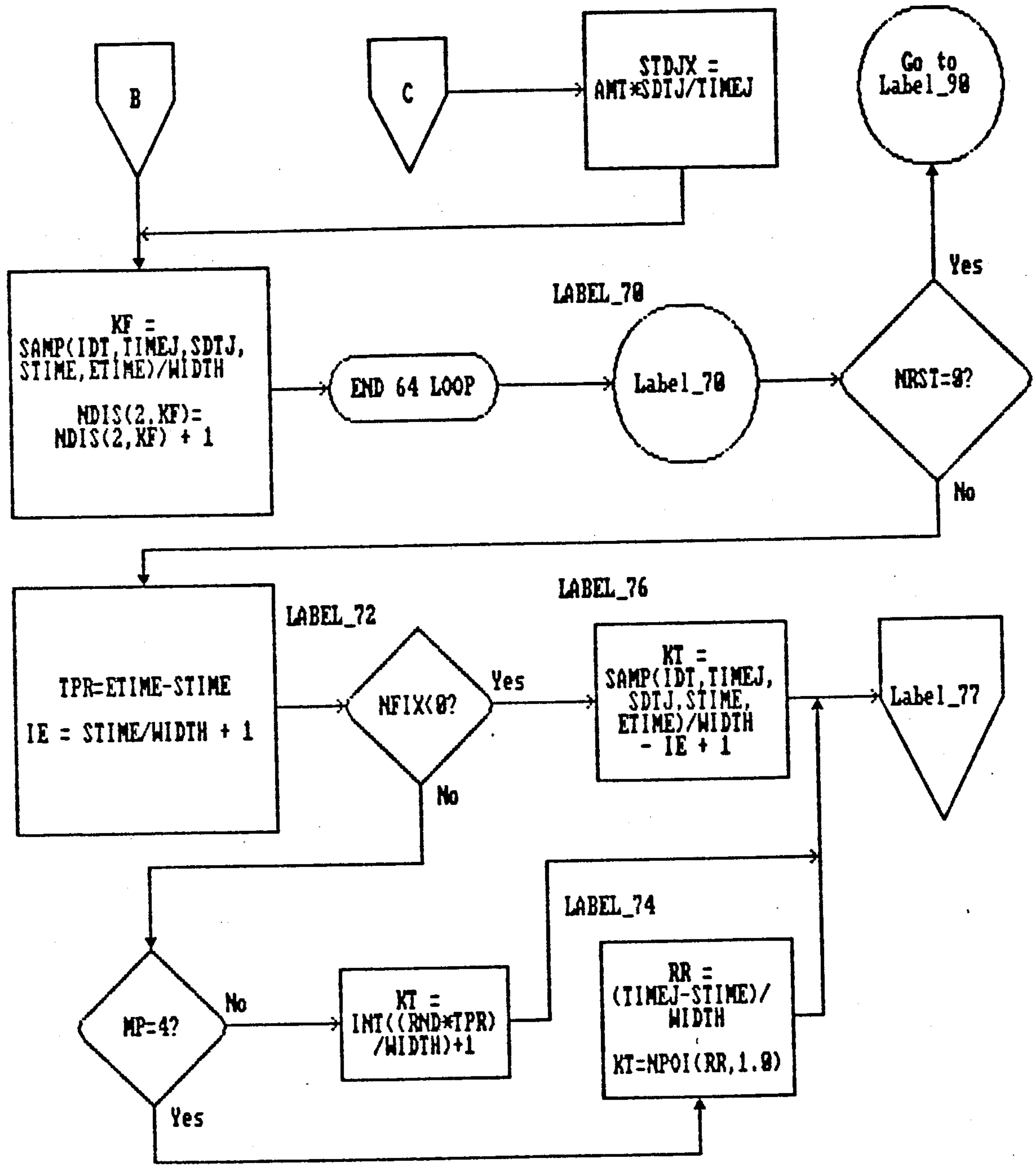


Figure 16. Transient Model Flowchart (continued)

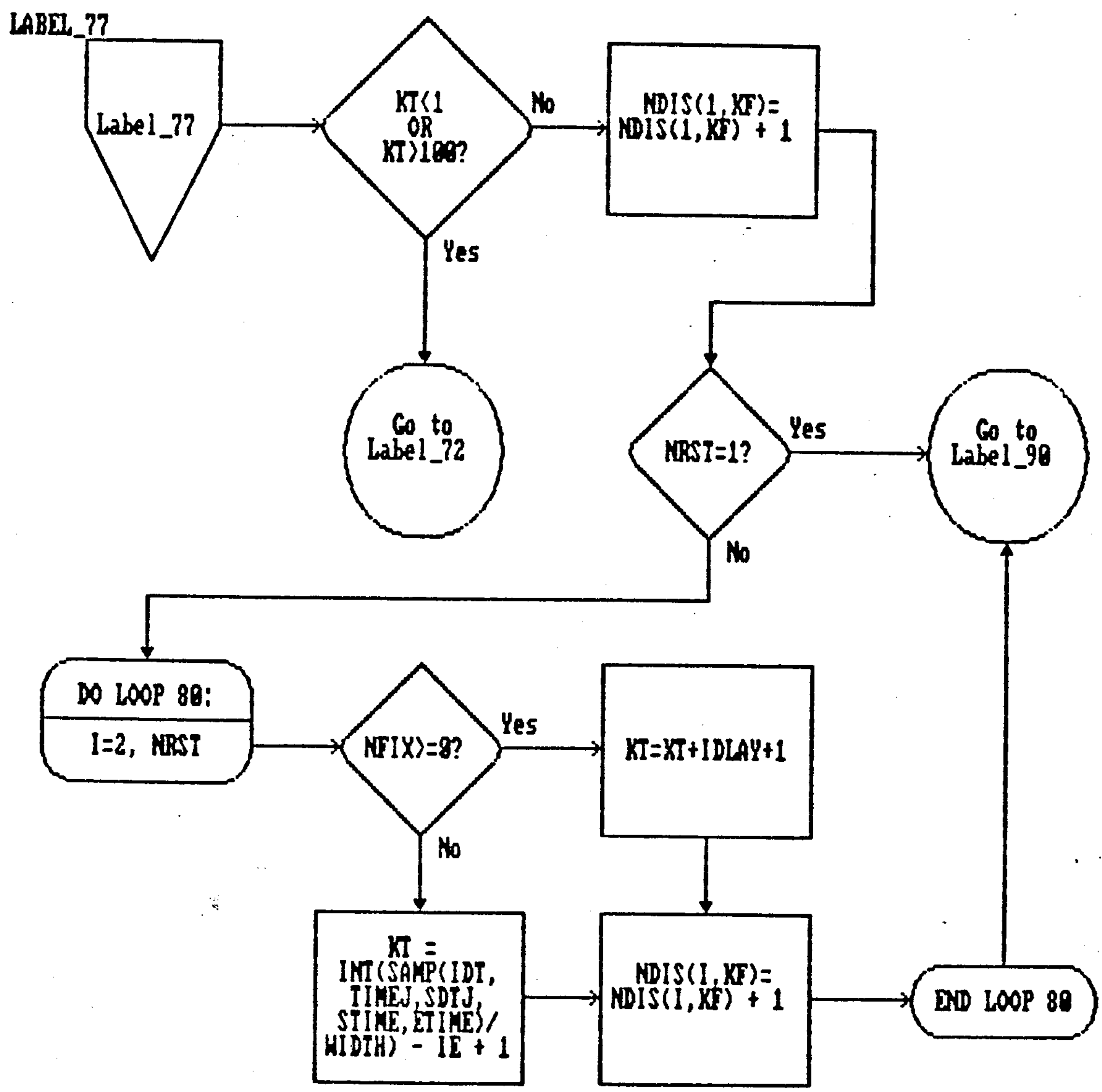


Figure 16. Transient Model Flowchart (continued)

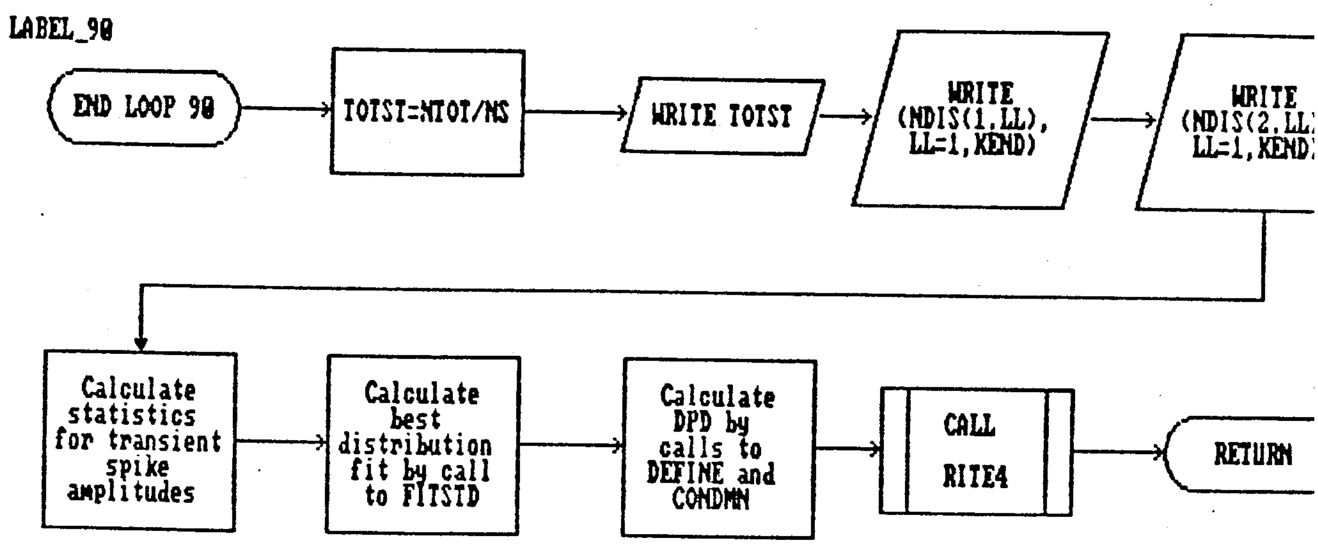


Figure 16. Transient Model Flowchart (continued)

5.2.5 Transient Load Model Sample Calculation

A sample problem which uses all of the available options was run. This was not meant to be a physically realistic run, but rather was used to demonstrate these options.

All mission phases were constructed to be five seconds in duration and the Poisson arrival rate in each case where this model is used was 0.6, i.e. a mean arrival rate of 3 events per five second interval. The spike width for all cases was given as 0.25 seconds and a delay time of two spike widths (0.5 seconds) was used. Subsequently, five mission phases were defined. The first phase used the Poisson model with no fixed spikes. The second phase also used the Poisson model, but included two fixed spikes. The third mission phase used the Poisson model, but the spikes were forced to occur in a Gaussian distribution about 12.5 seconds with a standard deviation of 0.25. (This is the NFIX less than zero option). The fourth phase was the final transient phase and used the uniform model with the maximum number of peaks equal to 3. The final phase was a quasi-steady state phase which went from 65% to 104% power levels. This phase was included to check that there was a correct time phasing between the models. Figure 17 shows the results.

As Figure 17 indicates, the transient model appears to be working well. The Poisson Model shows peaks occurring in a manner which is expected. The second mission phase, between 5 and 10 seconds, shows the variance getting smaller near 7.5 and 8 seconds. This is expected because there are two fixed peaks at these times whose mean time of occurrence is equal to these values. The uniform model, used between 15 and 20 seconds, also behaves as one would expect, since the time of a peak occurrence is equally likely anywhere in this phase.

The fourth phase, where the number of peaks behaves a Poisson arrival rate model, but the timing is within a specified distribution, is expanded and shown in Figure 18. In this figure one can more clearly see the load prediction follows the base curve, with no variation, until 11.75 seconds at which time the load shows a sharp increase and associated variability. This ends at 14.0 seconds. This is precisely the expected result since 11.75 second is three standard deviations away from the mean time of occurrence it would not be likely to see any spike values occurring until after that time. The peak at 12.5 seconds is exactly where it should be and the smaller peaks at 13.0 and 13.5 seconds are also seen. Therefore, it is concluded that the model is working as planned.

As a final test case, the entire probabilistic load model was run using the Poisson transient model with no fixed spikes from 0 to 2.5 seconds, and a quasi-steady state calculation from 65% to 104% power from 2.5 seconds to 10 seconds. These results are shown in Figure 19. Again, the model behaves as expected.

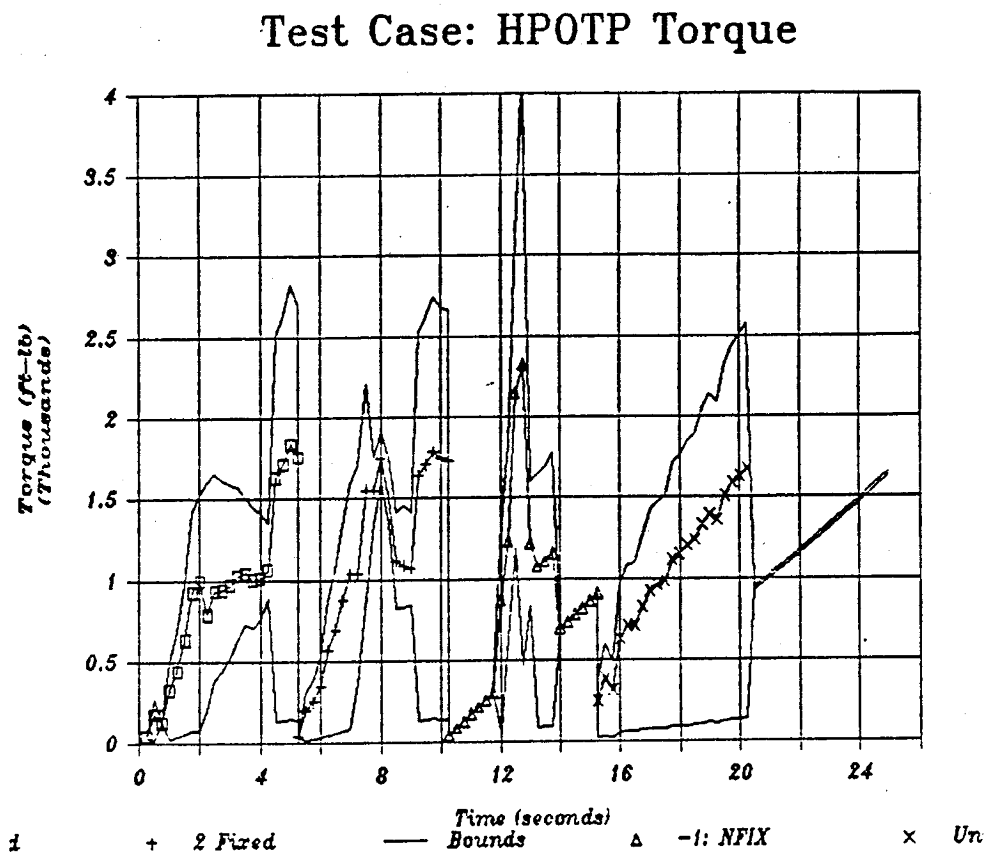


Figure 17. Sample Transient Calculation: Five Mission Phases

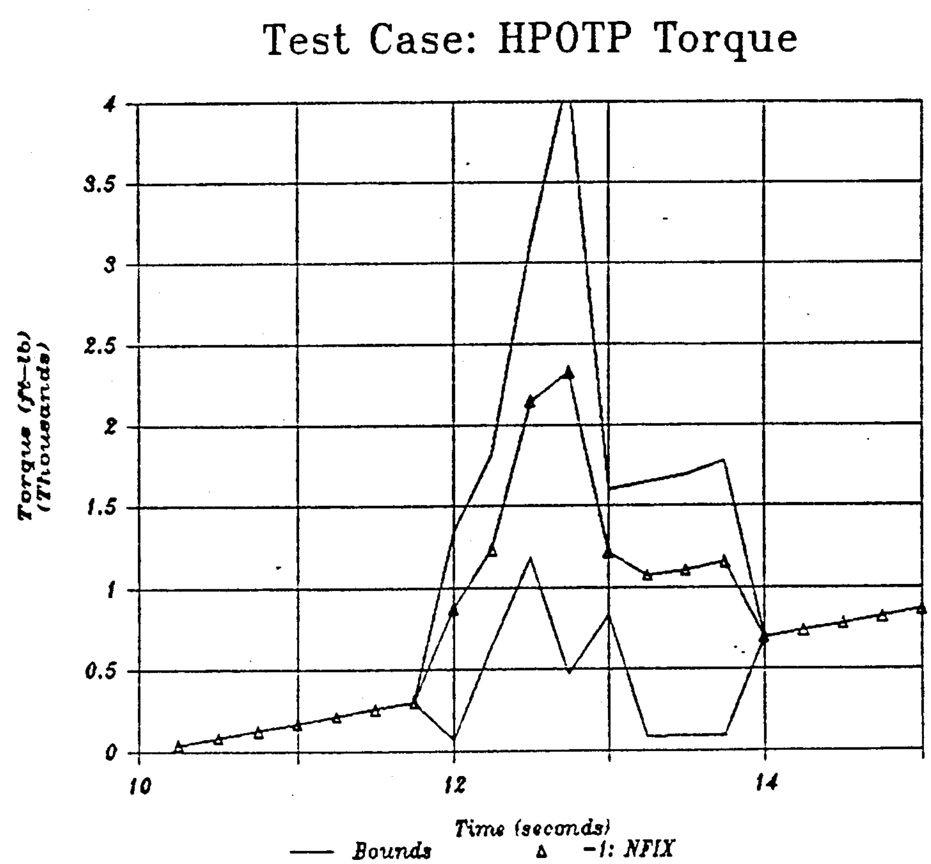


Figure 18. Poisson Transient Model With NFIX = -1

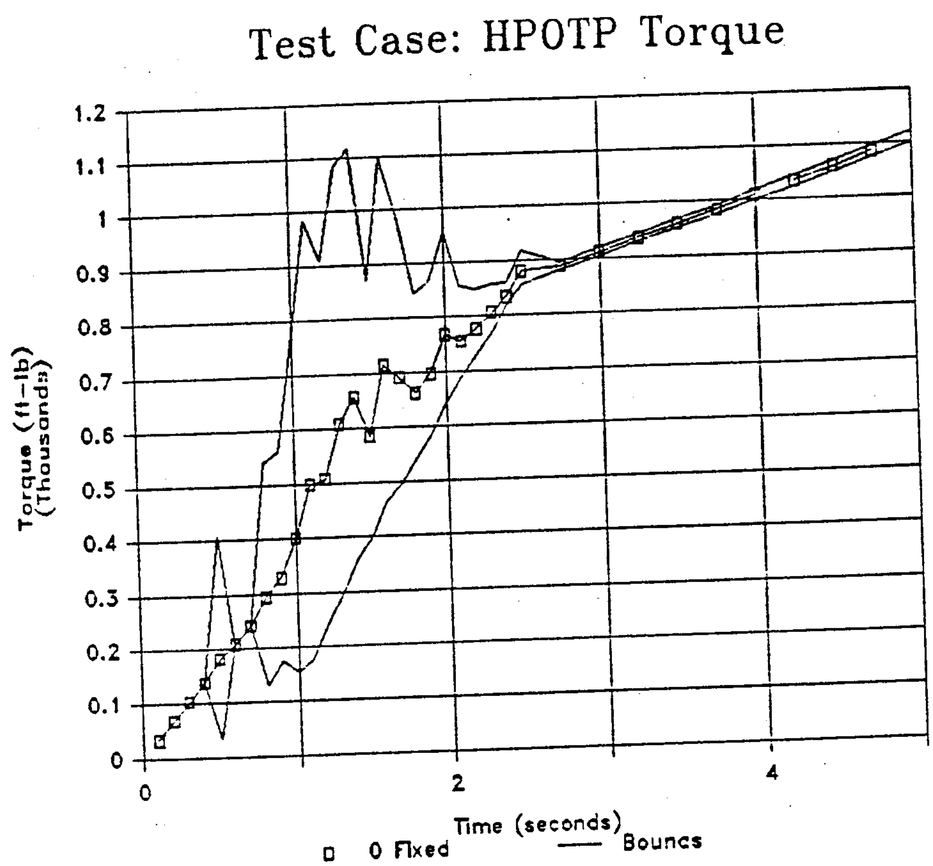


Figure 19. ANLOAD Calculation For HPOTP Torque

5.3 Periodic Load Model

The modeling of vibration or, more generally, periodic loads, requires that a more rigorous treatment of dependent load models be developed. This is because the forced vibration loads, especially at multiples of pump speeds (in the frequency domain) show a strong dependency to each other. The variability in the predicted load will also be incorrect if the dependency effect is not accounted for in the model. In fact, when the correlation is positive, the variability will always be under predicted. Therefore, a more thorough treatment of these types of loads has been developed.

5.4 Model Development

The basic model requires some estimates of the correlation between various types of vibration loads. These correlations are then used to predict the spread in the variable of interest. As an example, assume that one is interested in the composite vibration load, where the composite load is composed of all of the synchronous and random levels for all frequencies. (The "loads" that will be predicted are PSD levels.) The composite load, denoted C, is given as a function of a constant term and the synchronous vibration magnitudes:

$$C = a_0 + a_1 L_1 + \ . \ . \ . \ + a_m L_m \qquad (1)$$

where L_i is the magnitude of the i^{th} synchronous level and the coefficients, a_i, are to be determined. It is worth noting that this can just as easily be written as the first synchronous load, L_1, as a function of the composite level, C, but this is the example chosen for discussion.

For the model shown in Equation (1), how does one predict the composite levels? To do this we will need to compute the covariance matrix of the individual inputs, L_i, of the model. But first it is wise to adopt some additional notation and normalize some terms.

First we denote the normalized load levels as N_i and calculate N_i as:

$$N_i = (L_i - m_i)/s_i \qquad (2)$$

where m_i is the mean of L_i and s_i is the standard deviation. The actual equation which will be fit is then given by:

$$C = c_0 + b_1 N_1 + \ldots + b_m N_m \qquad (3)$$

If we denote the variance of C by Var(C) then

$$\mathrm{Var}(C) = b^T R\, b \qquad (4)$$

where b is the vector composed of the coefficients in Equation (3) and R is the matrix of the correlation coefficients, r_{ij}, between variable L_i and L_j.

At this point we take advantage of some useful properties of the covariance matrix, R. We know that the matrix Q, whose columns consist of the eigenvectors of R can be used to reduce Equation (4) to the form:

$$\mathrm{Var}(C) = \sum q_i p_i^2 \qquad (5)$$

where q_i are the eigenvalues and p_i are the components of the vector obtained by multiplying b times Q^T.

To perform calculations using these equations, it becomes necessary to examine the available data to obtain estimates for m_i and s_i, i.e. the mean and standard deviations for the i^{th} synchronous load level.

Most of the available data deals with maximum PSD values over the test or mission. These values are used to monitor the wear and health of various engine components, but leave out some of the statistical information which is needed. Therefore, the probabilistic information is obtained from the database assuming that the peak values represent a three standard deviation spread from the mean value. A visual examination of tracking filter data indicates that a COV value is approximately 20%. This implies that the mean and standard deviation values can be found from the following set of equations:

$$\text{Mean} = 0.625 \times \text{Peak amplitude} \tag{6a}$$

$$\text{Standard deviation} = 0.125 \times \text{Peak amplitude} \tag{6b}$$

Of course, it is assumed that the PSD values are distributed normally about their mean values. The peak amplitudes are obtained from data analyses. Figure 20 shows the distribution of peak values for both pump and turbine data for 104% and 109% power levels. This data represents the HPFTP peak PSD data where an eleven point moving average has been used. It is interesting to note that the 109% power level curve is to the left of the 104% power level curve.

The other factor to examine is the variability in the vibration type load with location. Figures 21 through 24 show this variation for composite and synchronous pump data at both 104% and 109% power level. The turbine data has also been examined but the plots do not provide any new information and so they are not included.

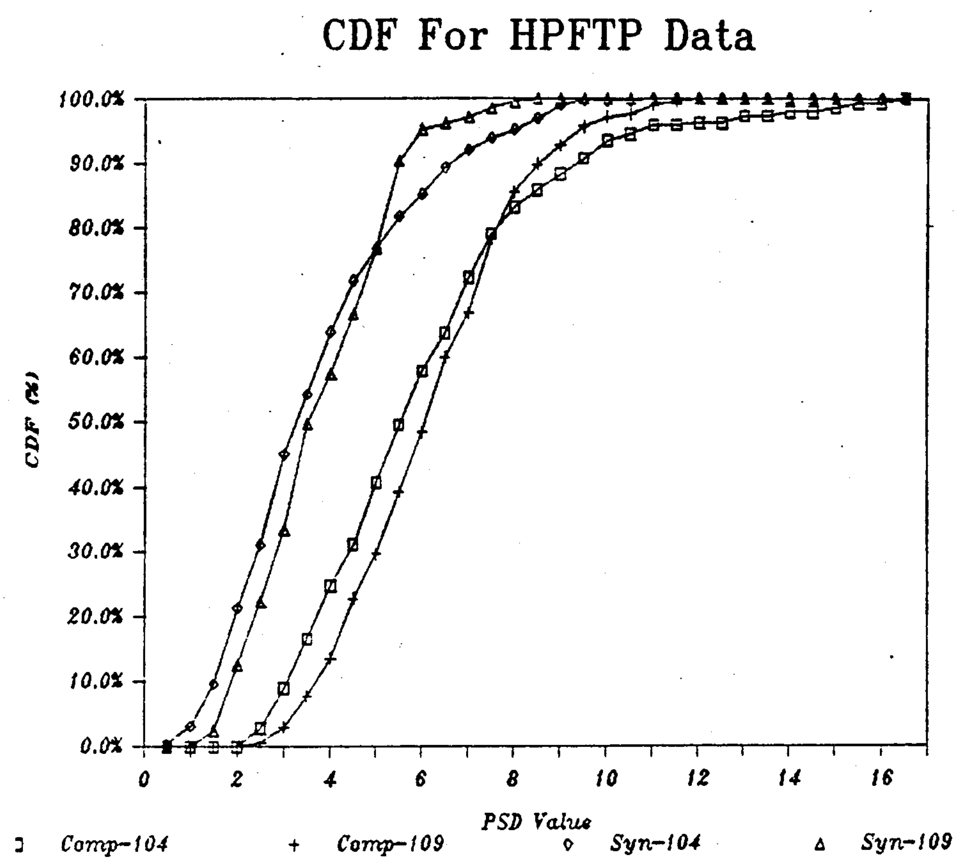


Figure 20. Cumulative Distribution Functions For Peak PSD Values

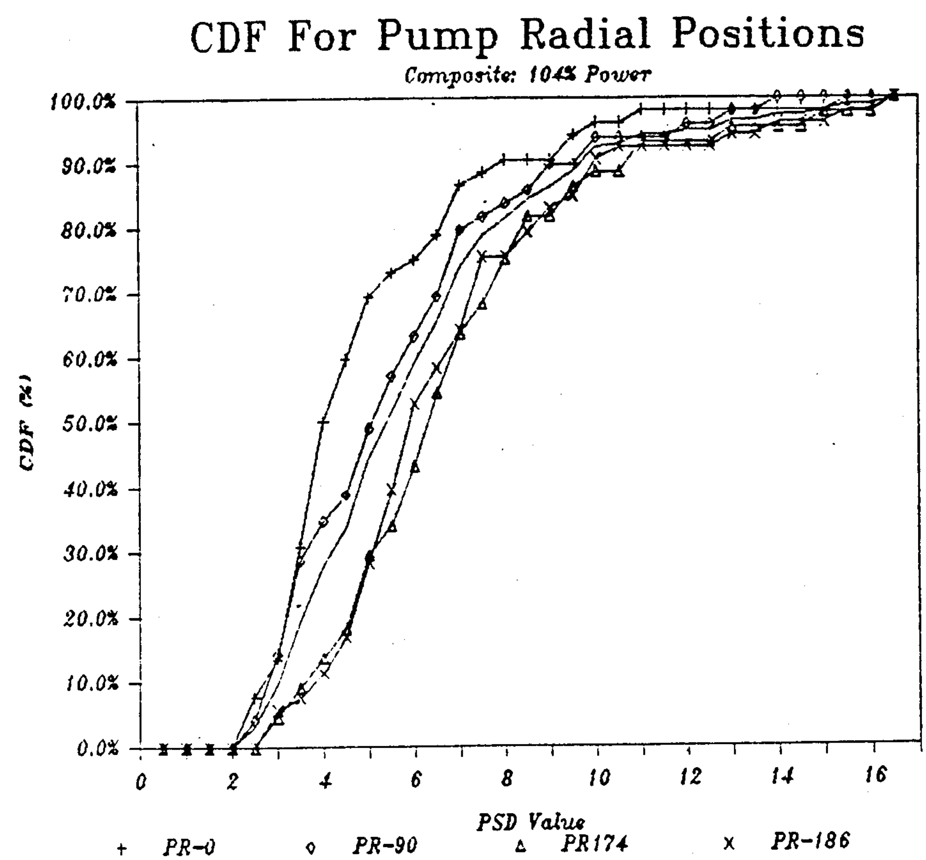


Figure 21. Cumulative Distribution Functions For Differing Pump Locations – Composite 104% Power

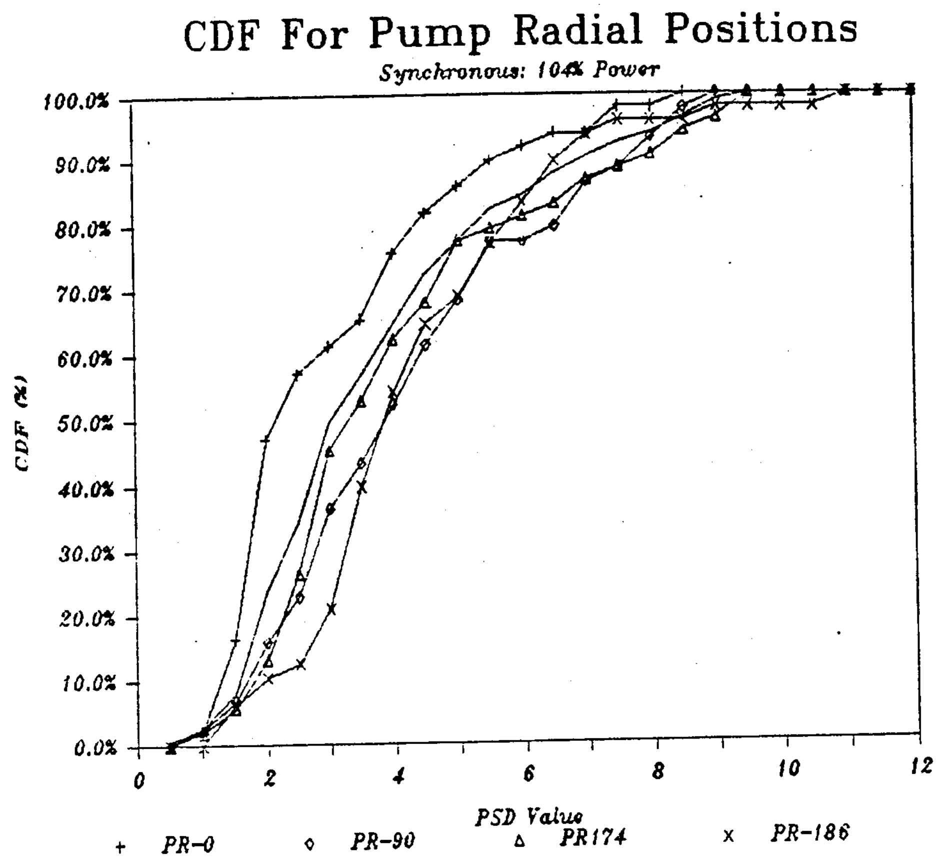


Figure 22. Cumulative Distribution Functions For Differing Pump Locations - Synchronous 104% Power

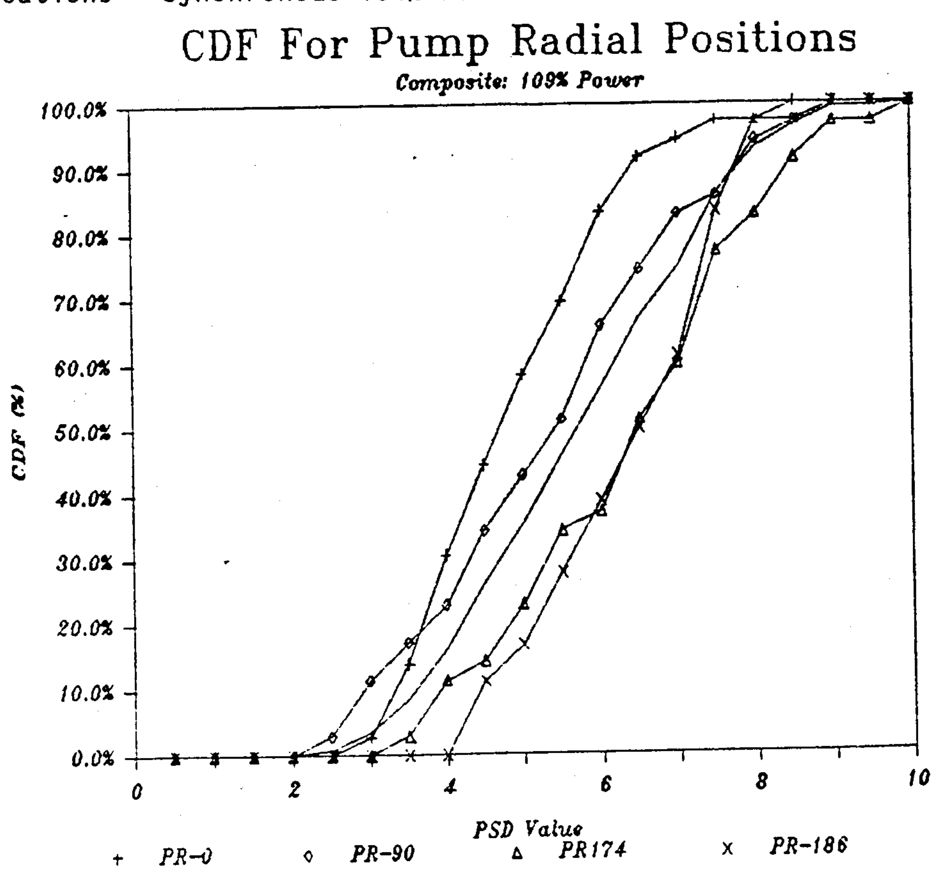


Figure 23. Cumulative Distribution Functions For Differing Pump Locations - Composite 109% Power

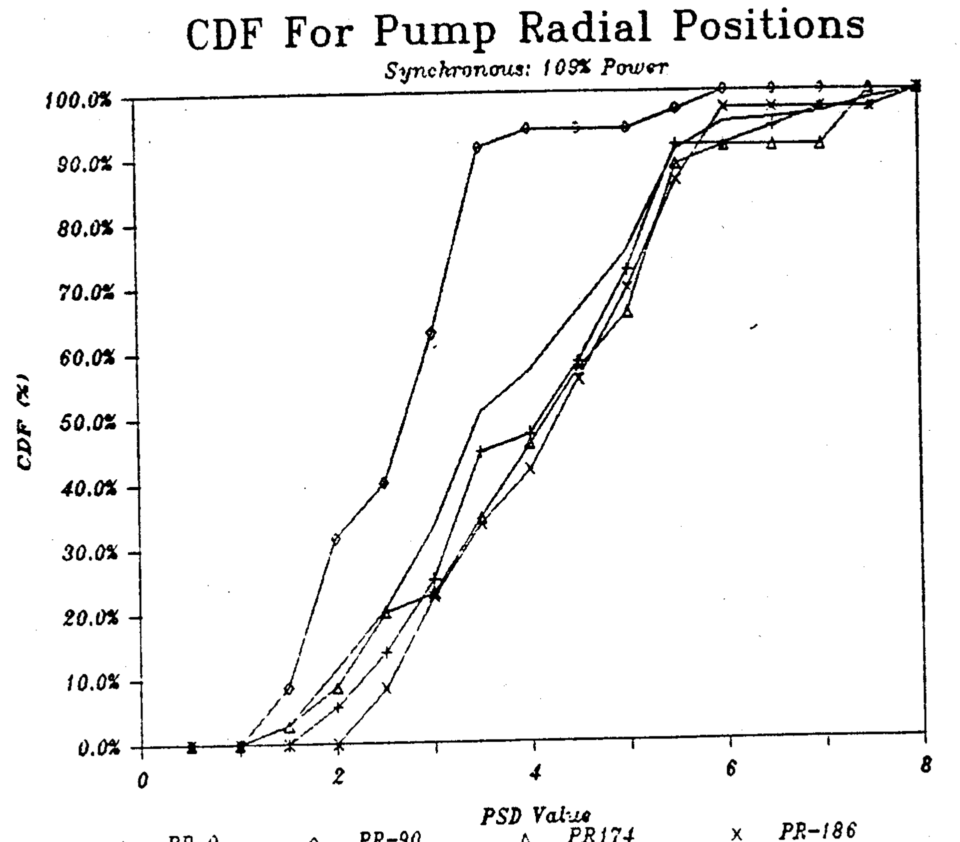


Figure 24. Cumulative Distribution Functions For Differing Pump Locations - Synchronous 109% Power

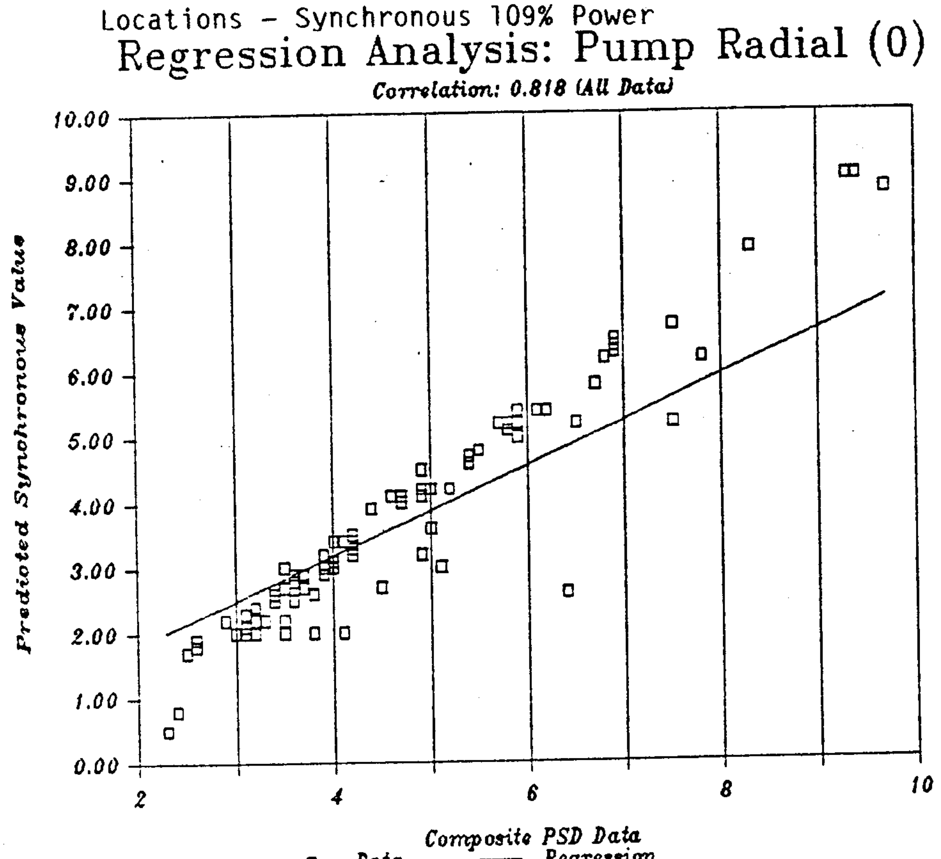


Figure 25. Composite And Synchronous Correlation For All Power Levels - All data

This information is useful for obtaining the peak amplitudes for the vibration loads either for pumps or turbines and adjusting for location. However, the peak amplitudes cannot be obtained as independent random variables, as has been done previously, since there is a high degree of correlation between some of the synchronous modes. The correlation of the peak composite data with the peak synchronous data is shown in Figures 25, 26, and 27. The correlation of the composite and synchronous data has a correlation coefficient of 0.818 when all of the power level data is included, 0.797 for the 104% power level data, and 0.987 for the 109% data, for the pump radial position (0). The other correlation coefficients for the remaining locations are shown in Table 8. The plots of these remaining data sets do not show any new information just more or less scatter about the trend lines and therefore they are not included.

New information is obtained when higher multiples of the pump or turbine speeds are examined. For the 2N, 3N, and 4N multiples there is little correlation among the peak amplitudes. This is shown in Figures 28 and 29. In Figure 28 we see the same plot as in Figure 26 but now the 2N data is superimposed on top of that plot. As this Figure indicates, there is a clear relationship between the composite and synchronous data, but a very weak one between the composite and the 2N data. The relationships between higher multiples is even weaker as Figure 29 indicates.

At this point it is noted that after this analysis was performed it was discovered that the data for the PSD's found in Table 9 were taken only through 850 hertz. This implies that a significant portion of the energy imparted to the engine due to the 2N, 3N, and 4N forced vibration levels is not represented in the PSD values.

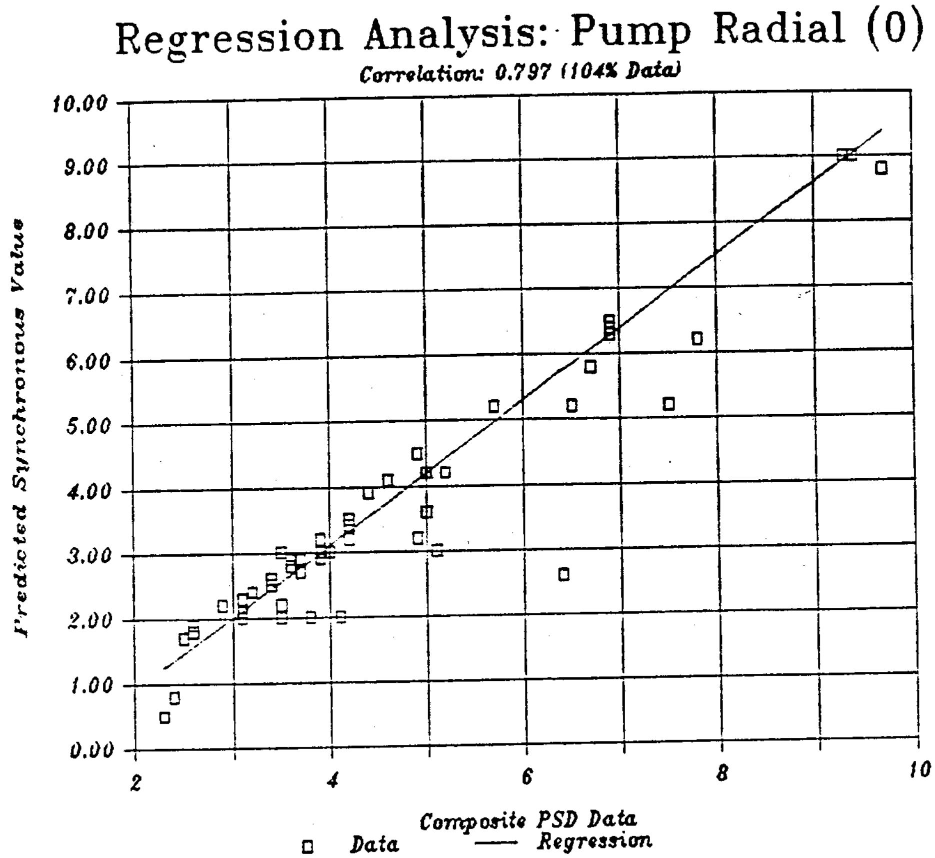


Figure 26. Composite And Synchronous Correlation For 104% Power Levels

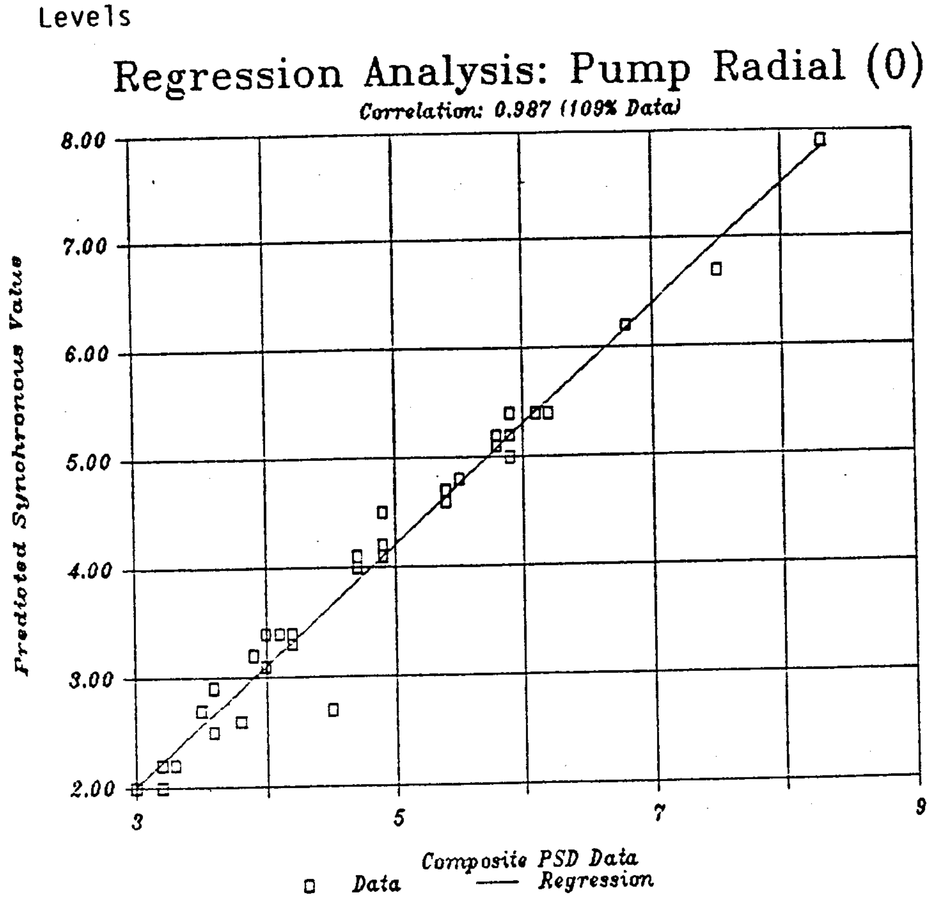


Figure 27. Composite And Synchronous Correlation For 109% Power Levels

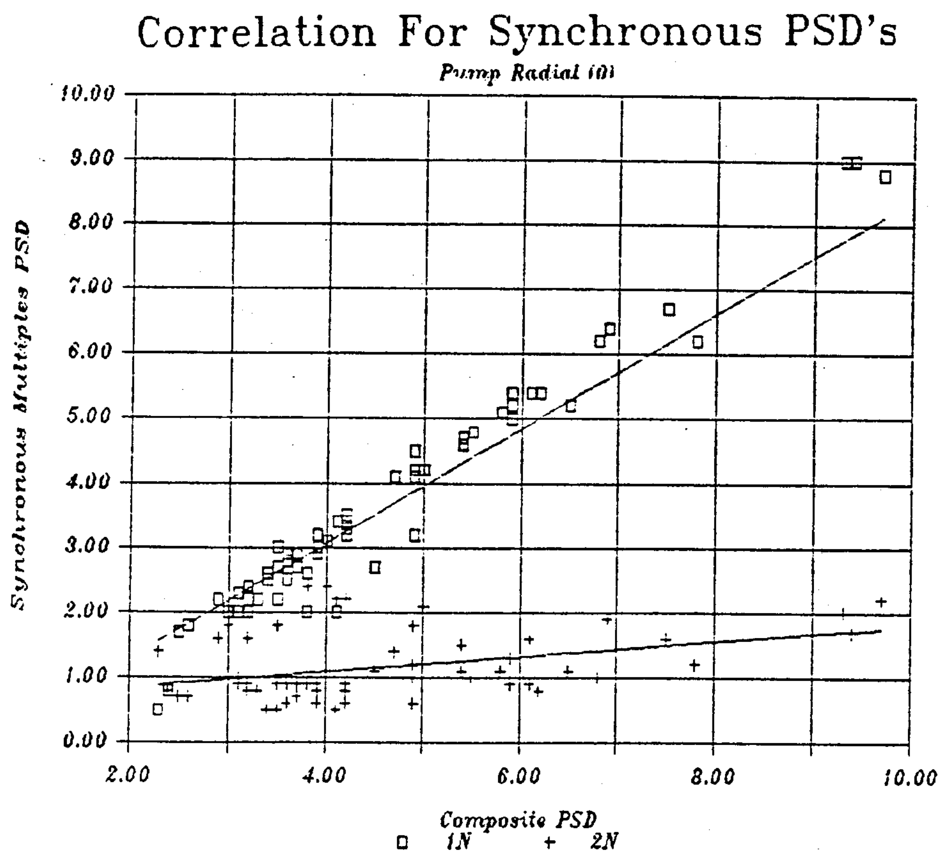


Figure 28. Correlation Of Higher Multiple Synchronous Data

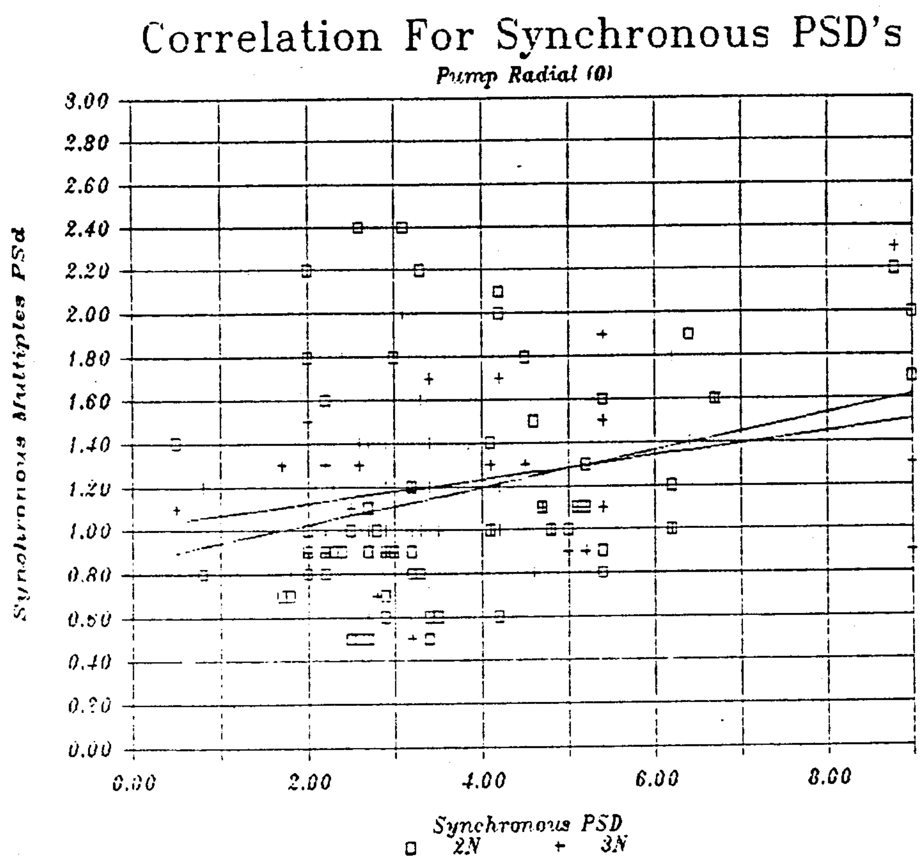


Figure 29 . Correlation Of Higher Multiple Synchronous Data

Table 8

Correlation Coefficients Between Composite And Synchronous Data

Location	Correlation Coefficient		
	All Data	104% Power	109% Power
Pump Radial (0)	0.818	0.797	0.987
Pump Radial (90)	0.740	0.761	0.657
Pump Radial (174)	0.719	0.693	0.845
Pump Radial (186)	0.729	0.735	0.819
Turbine Radial (90)	0.554	0.594	0.491
Turbine Axial	0.874	0.873	1.000**
Turbine Radial (180)	0.642	0.702	0.661

** Only two data points were in this data set, the remaining sets had as few as 21, and as many as 63.

While this is a problem for calculating the coefficients that will ultimately be contained in the expert system, it is not a problem for the purposes of this sample calculation. What will be changed when the complete frequency range is changed is the coefficients in the matrix R. However, a change in the numerical values will not affect the methodology.

To provide additional clarification of the steps taken so far, a sample calculation is performed. The data for this calculation is shown in Table 9 where the composite, synchronous, and pump multiple forced vibration loads, through four times the pump speed (4N), are shown. These data were analyzed to produce the correlation coefficients shown in Table 10. The data shown in Table 9 is the peak amplitudes measured during 63 separate tests. There are additional tests available for the composite and synchronous levels, but the data were missing for higher multiples. Since we are concerned with developing correlations, only these 63 tests were used. Ultimately, the actual PSD levels used in the vibration model will be transformed by Equation (6) where it is assumed that these peaks are at the 3-sigma level.

During the first phase of this program there are no physical model requirements for the vibration model. Therefore, the probabilistic synthesis of the individual components into an overall composite, random vibration load is being accomplished by a simple linear fit:

$$\text{Composite} = a_0 + a_1{*}L_1 + a_2{*}L_2 + \cdots + a_n{*}L_n \quad (1)$$

where L_i are the individual synchronous loads and a_i are the coefficients obtained from regression analysis. The variability in the composite load can then be obtained, using the variance as a measure of the variability from the covariance matrix:

$$\mathrm{Var}(C) = b^T \; R \; b \qquad (4)$$

where b is the vector of normalized coefficients (b_1, ..., b_n), and R is the covariance matrix. The covariance matrix is made up of elements given by:

$$C_{ij} = r_{ij} s_i s_j \qquad (7)$$

TABLE 9. Vibration Load Data Used For Sample Calculation

Composite	Synchronous	2N	3N	4N
2.3	0.5	1.4	1.1	0.9
2.4	0.8	0.8	1.2	1.9
2.5	1.7	0.7	1.3	0.7
2.6	1.8	0.7	0.8	1.0
2.9	2.2	1.6	0.9	0.9
3.0	2.0	1.8	0.9	0.9
3.1	2.3	0.9	1.2	1.2
3.1	2.0	1.0	1.5	1.0
3.2	2.2	1.6	0.9	1.1
3.2	2.4	0.6	1.7	0.9
3.2	2.0	0.8	0.8	2.3
3.3	2.2	0.8	1.0	0.9
3.4	2.5	0.5	1.1	1.0
3.4	2.6	0.5	1.4	1.3
3.5	2.7	0.5	0.6	1.0
3.5	3.0	1.8	0.9	1.4
3.5	2.2	0.9	1.3	1.9
3.6	2.8	1.0	0.7	0.8
3.6	2.9	0.9	0.9	0.6
3.6	2.9	0.6	1.0	0.8
3.6	2.5	1.0	1.1	1.9
3.7	2.9	0.7	1.4	0.8
3.7	2.7	0.9	1.4	0.8
3.8	2.6	2.4	1.3	1.0
3.8	2.0	0.9	1.0	0.7
3.9	2.9	0.6	1.2	1.6
3.9	3.2	0.8	0.5	0.7
3.9	3.0	0.9	1.8	1.1
4.0	3.1	2.4	2.0	1.4
4.1	2.0	2.2	1.4	1.7
4.1	3.4	0.5	1.4	1.2
4.2	3.3	2.2	1.6	0.9
4.2	3.2	0.9	1.0	1.2
4.2	3.4	0.6	1.2	1.5
4.2	3.3	0.8	1.0	1.4
4.2	3.4	0.9	1.8	0.8
4.2	3.5	0.6	1.0	1.0
4.5	2.7	1.1	1.0	1.0
4.7	4.1	1.4	1.0	3.3
4.9	3.2	1.2	1.2	1.4
4.9	4.5	1.8	1.3	2.1
4.9	4.2	0.6	1.0	1.0
4.9	4.1	1.0	1.3	1.9
5.0	4.2	2.1	1.2	1.4

TABLE 9. (Concluded)

Composite	Synchronous	2N	3N	4N
5.4	4.7	1.1	1.1	0.9
5.4	4.6	1.5	0.8	0.9
5.5	4.8	1.0	1.0	1.2
5.8	5.1	1.1	1.1	1.0
5.9	5.0	1.0	0.9	0.8
5.9	5.2	1.3	0.9	1.0
5.9	5.4	0.9	1.9	1.0
6.1	5.4	1.6	1.5	1.0
6.1	5.4	0.9	1.1	1.1
6.2	5.4	0.8	1.9	1.4
6.5	5.2	1.1	1.1	0.9
6.8	6.2	1.0	1.0	0.6
6.9	6.4	1.9	1.4	1.0
7.5	6.7	1.6	1.6	0.9
7.8	6.2	1.2	1.8	0.9
9.3	9.0	2.0	1.3	1.0
9.4	9.0	1.7	0.9	1.2
9.7	8.8	2.2	2.3	1.6
10.8	4.2	2.0	1.7	1.7

where r_{ij} is the correlation coefficients between variables i and j, s_i is the standard deviation of variable i, and s_j is the standard deviation for variable j. This provides a first approximation model for the composite, periodic load spectrum.

Before proceeding with additional calculations, it is necessary to first describe the numerical procedure used and how the eigenvalues and eigenvectors are determined.

5.4.1 The Calculation Of Eigenvalues And Eigenvectors

The eigenvalue and eigenvector calculation is performed numerically using the Leverrier method as modified by Faddeeva (Ref. 3). This method was selected because it simultaneously calculates the eigenvalues, eigenvectors and inverse matrix of eigenvectors. It is somewhat of a brute force technique but is robust--just the type of method that is needed for generic applications.

For the R matrix, shown in Table 10 in rows 2 through 5 and columns 2 through 5, the eigenvalues and eigenvectors which were calculated are shown in Table 11. Because the covariance matrix is real and symmetric, a simple check of the accuracy of the calculation can be made. This check is performed by multiplying the eigenvector matrix, Q (shown in Table 11) by its transpose. This should produce the identity matrix. The calculation demonstrated four significant figures after the decimal point which was judged to provide the needed accuracy for these calculations.

TABLE 10. Correlation of Vibration Loads

With:	Correlation of: $\underline{C}$	$\underline{L}_1$	$\underline{L}_2$	$\underline{L}_3$	$\underline{L}_4$
C	1	0.903062	0.405069	0.343665	0.030434
L_1	0.903062	1	0.329034	0.273249	0.038454
L_2	0.405069	0.329034	1	0.274478	0.147398
L_3	0.343665	0.273249	0.274478	1	0.087954
L_4	0.030434	0.038454	0.147398	0.087954	1

TABLE 11. Eigenvalues and Eigenvectors for Sample Calculation

Eigenvalues:			
1.62570E+00	9.78083E-01	7.43709E-01	6.52502E-01
Eigenvectors:			
Q_1	Q_2	Q_3	Q_4
5.56692E-01	-3.12676E-01	3.92960E-01	-6.61853E-01
5.85605E-01	2.03978E-02	3.86287E-01	7.12258E-01
5.34772E-01	-1.31845E-01	-8.34468E-01	1.68408E-02
2.47343E-01	9.40444E-01	5.24853E-03	-2.33145E-01

At this point we can begin the calculation for the variance of the composite load, Var(C). If we use the correlation coefficients of C with the forced vibration levels then these correlation coefficients represent the b_i in Equation (3). If we compare Equations (1) and (3), it is clear that in the calculation of the variance Vector b in Equation (4) must be changed to:

$$b' = (b_1 \cdot s_1, \ldots, b_m \cdot s_m)$$

Therefore:

$$\mathrm{Var}\,(C) = \sum b^2 \cdot s_i \cdot q_i \cdot s_i \qquad (8)$$

The mean values and the standard deviations calculated from the data are shown in Table 12. Using these values for the standard deviation, s_i, the correlation coefficients from Table 10 for the composite with the four synchronous levels for b_i, and the eigenvalues from Table 11 for q_i, the variance of the composite level is found to be:

$$\mathrm{Var}(C) = 3.08682$$

Taking the square root yields an estimate of the standard deviation for the composite load of 1.745 which compares very well with the value of 1.826 found from the data analysis. However, in general, we do not expect agreement that is this close because the entire frequency range has not been included. To check, the entire analysis was repeated for the pump radial position (90). For this analysis, the calculated standard deviation for the composite vibration PSD is 1.435 while the data analysis gave a result of 1.852. While these are of the same order, we would expect the agreement to improve as more of the frequency range is included.

This expectation arises because the covariance matrix did not include all of the cross-correlations and, thus, the estimated variance should be low (for positive correlation). However, the standard deviations should not match exactly because there is still one other source of variability that has not been accounted for in the analysis. This source of variability is the random component of the periodic load.

To account for the random portion of the composite PSD we modify Equation (3) to include this component:

$$C = c_0 + b_1N_1 + \ . \ . \ . + b_mN_m + b_{m+1}Z \qquad (3a)$$

TABLE 12. Mean and Standard Deviations for Vibration Data

	Composite	Synchronous	2N	3N	4N
Mean:	4.719047	3.711111	1.171428	1.215873	1.180952
Standard Deviation	1.825903	1.795772	0.528678	0.356440	0.463546

where Z is the random component. Because the random component must, by definition, be uncorrelated with all of the other modes, the covariance matrix will have another row and column added that contains all zeroes except the $r_{m+1,m+1}$ component which will be equal to 1. That is, the new covariance matrix, denoted R', is given by:

$$R' = \begin{matrix} r_{1,1} & r_{1,2} & \cdots & r_{1,m} & 0 \\ r_{2,1} & r_{2,2} & \cdots & r_{2,m} & 0 \\ & & \vdots & & \\ r_{i,1} & r_{i,2} & \cdots & r_{i,m} & 0 \\ & & \vdots & & \\ r_{m,1} & r_{m,2} & \cdots & r_{m,m} & 0 \\ 0 & & \cdots & 0 & 1 \end{matrix}$$

It is a well known fact from linear algebra that this modification to the covariance matrix will leave the original eigenvalues and eigenvectors unchanged. It will introduce a new eigenvalue equal to 1 and an eigenvector equal to the identity matrix column. Therefore $b_{m+1,m+1}$ will be equal to 1 and the variance of the random component can now be calculated from:

$$\mathrm{Var}(Z) = \mathrm{Var}(C) - \sum b^2\, s_i\, q_i . s_i \tag{9}$$

Table 13 presents the results of these calculations for a variety of pump and turbine positions. In some cases the variance of the composite PSD is less than the predicted value from the correlated data analysis. This is believed to be due to the restricted range of frequencies that used for the data collection, and is not indicative of the results which would be obtained from a more complete frequency spectrum. There is one interesting trend in the data that shows that the 90 degree positions for both the pump and turbine loads has a larger correlation contribution to the variance than the (approximately) 180 degree position. This may warrant further investigation when the frequency range is increased.

TABLE 13. Predicted Standard Deviation For Pump and Turbine Positions

	Predicted Standard Deviation		Data	Random
Position	Uncorrelated	Correlated	Std Dev	Component
Pump (0)	1.62501	1.74486	1.8259	0.538
Pump (90)	1.11564	1.43547	1.8524	1.171
Pump (174)	1.62559	1.80987	1.7753	
Pump (186)	1.45744	1.66173	1.6495	
Turb (90)	1.51948	1.94646	2.3961	1.397
Turb (180)	0.80206	0.91088	1.6075	1.325

5.4.2 Changing The Peak Values to Nominal Values

All of the calculations preformed to this point have been for the peak value data. As was previously discussed, the mean and standard deviation for the nominal PSD levels are calculated using Equation (6). Now, we can simply estimate the variance of the composite load for the nominal conditions using this equation. Therefore, the standard deviation is changed by dividing by 8 and the new variance of 0.38585 is obtained.

This model has been used to compare its prediction with the available data. A typical plot is shown in Figure 30. In this figure, the actual data is compared to the prediction obtained from RASCAL. The mean predictions remain accurate but the standard deviation, or spread in the data is under predicted. This is primarily due to the limited number of samples available from these runs. The cases are being re-analyzed to determine if the smaller predicted variability is due to the method, or the need to increase the sample space selected for the analyses.

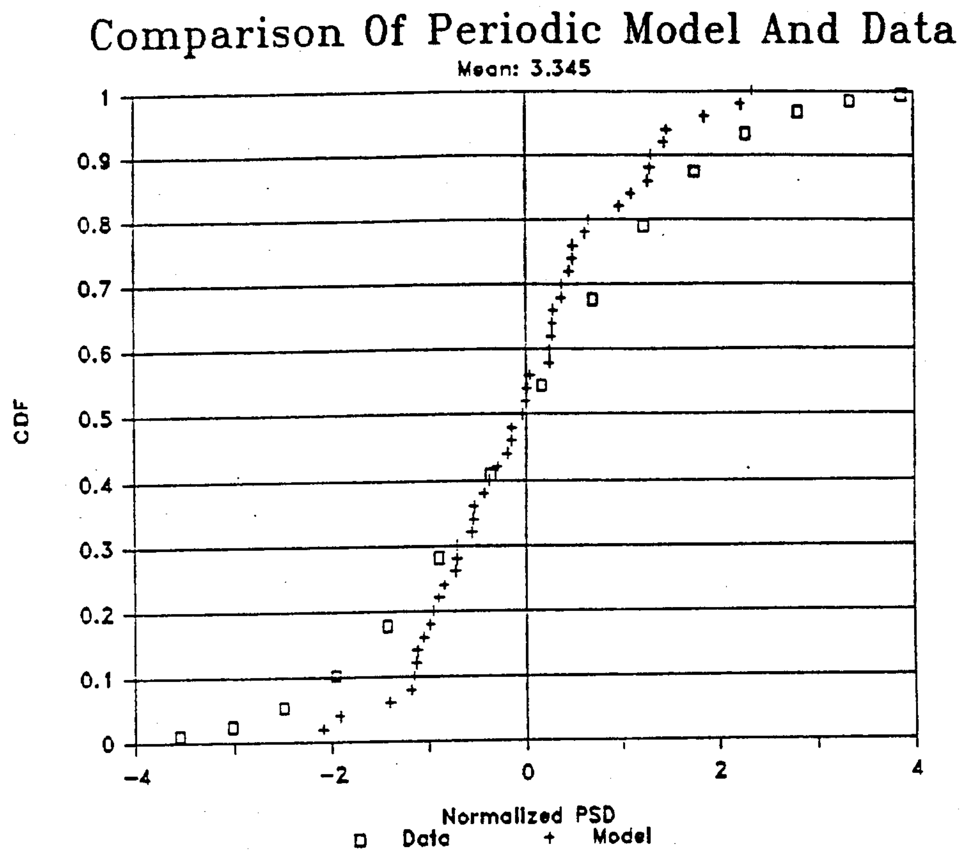


Figure 30. Comparison Of MSFC Pump Rad (0) Data And Model Prediction

5.5 Probabilistic Methods Validation

5.5.1 Probabilistic Model Testing

Because of concerns raised about the programs ability to deal with non-normal distributions a test case was run to insure that all of the distributions included in the program function as intended. Each distribution was tested using the commanded mixture ratio as input with a mean of 6.0 and a standard deviation of 0.01. Each distribution was obtained consistent with these inputs and is shown in the attachment. However, it was believed that it is important to reduce any confusion about the parameters meaning and/or definition, a new option was added to the program. If a negative value is input for the distribution type the program assumes that parameter 1 represents the mean value and parameter 2 represents the standard deviation. The program then calculates the necessary parameters for the distribution type requested. For example if one input a value of -3 for the distribution type and 10.0 for parameter 1 and 1.0 for parameter 2 then the program would assume a mean of 10. and a standard deviation of 1. and calculated the lognormal parameters (because the distribution type is 3) of 2.2976 and 0.099751 for the distribution parameters to be used in the subsequent calculations. This should increase the ease of using the program.

5.5.2 Changes In The Probabilistic Model

The probabilistic methodology is continually being updated outside of this program. Currently, the RASCAL methodology uses differing bin sizes to further increase computational efficiency. This feature was incorporated into the NASA load model. It is currently being tested to assess its effect on the computational efficiency of the computer program.

5.5.3 Dependent Load Generic Engine Modifications

The table look-up method for adjusting the results of the load calculations for the calculation of generic engine results was incorporated into the model. The modifications include a table look-up multiplication factor for the dependent loads so that they can be scaled. Currently, the model only includes scale factors for SSME. Other engine type will be added as they become available.

6.0 THE LOAD EXPERT SYSTEM: LDEXPT VERSION 2.0

6.1 Summary

The load expert system LDEXPT version 2.0 was implemented on the NASA/LeRC's VM system in June 1987. Since then it has been tested and utilized to implement the composite load spectra model. The expert system has two subsystems, the rule-based management system (RBMS) and the knowledge-based management system (KBMS). The RBMS includes the expert system driver module and the rule modules. The expert system uses a decision tree inference algorithm. Each rule module is a decision tree with predefined processes running down different paths of the tree. The expert system interface prompts the user to make the selections. The KBMS includes a database system (DBMS) and a file input/output (I/O) module. The DBMS has been used to build and maintain the knowledge-base where the load information is stored. The I/O module takes care of the file I/O's. The system is well structured and heavily modularized. The different modules work harmoneously. During the last six months, several load models were added to the system with no difficulty. This is a direct result of the structured programming method employed throughout the project. The implementation of the database system to the load expert system proves to be a great success. The synergism of the expert system and the database system has elevated the power of the expert system many folds.

Figure 31 shows the modular structure of LDEXPT. SESUIM is the expert system driver which interfaces with the rule module, to perform different tasks. It interfaces with two auxiliary files: the problem text file and the rule file to generate queries and explanation. The rule modules access load information in the knowledge-base via the DBMS module. The load calculation module gets all information through the input file which can be generated manually or by the expert system rule module ANLDIN.

The load expert system with the database system in place completes the expert system building task for this phase of the project. The remaining tasks are to build the expert system's knowledge-base and to write rules for load spectra calculastions. The followings summarize the tasks performed this year:

LDEXPT: LOAD EXPERT SYSTEM

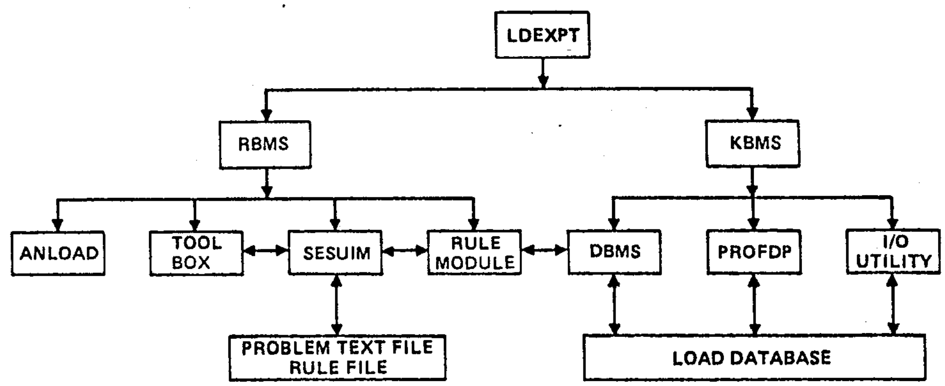


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Figure 31. LDEXPT: LOAD EXPERT SYSTEM

(1) Testing and debugging of the database system and the simple working memory model.

(2) Design of the rule modules for LDEXPT version 2.0.

(3) Implementation of the load expert system LDEXPT version 2.0 on the NASA/LeRC's VM system.

(4) Implementation of a plotting routine using LeRC's GRAPH3D package.

(5) Implementation of the direct file I/O option.

(6) Debugging of the turbine blade load scaling model for the pressure loads.

(7) Modification of the ANLOAD module to implement the infinitely large influence coefficient set option.

(8) Review and implementation of the transient models.

(9) Review and implementation of the thermal load models.

6.2 The Knowledge-Base

The implementation of the database system is one of the major improvements of the load expert system LDEXPT version 2.0 over the previous versions of LDEXPT. The database system provides an efficient representation of the load information. It allows the knowledge to be organized in an uniform format and in turn it greatly facilitates the knowledge retrieval process of the expert system.

Knowledge representation is a very important issue in designing a knowledge-based system. Any expert system without an efficient way of representing the domain knowledge and data is doomed to fail. Many in the market place have seen, as we have experienced that a database system interfaced with an intelligent system to become an intelligent database system is a very powerful system. The load expert system can be regarded as one such system.

The domain knowledge for the composite load spectra project is the load information, such as the kinds of load, engine components, the mean values etc., and the load models for load calculation. The load information can best be represented by databases for ease of update and maintenance. Normalized databases reinforce data integrity and remove data redundancy.

The database system implemented in the load expert system is a flat-file system. The database built by the system can be easily updated. The record can be selected with the values of key variables. The keys can be changed by rebuilding the database table. No relational calculus such as joining databases and intersecting databases has been built into the database system. At this time, there is no need of the expert system to use those database operations.

6.3 Knowledge Engineering

Knowledge engineering is the most important step in developing an expert system. With an appropriate knowledge representation knowledge engineering becomes a smooth sailing. As discussed in the last section, databases are used to store the load information and data. These information and data can then be easily retrieved and processed. The domain knowledge for the composite load spectra project includes the load information and the load generation knowledge. The load information covers the domain of engine system and its components, engine geometric data, load data and engine flight and test data. The load generation knowledge composes of the load modeling, the load generation procedure and the load calculation.

There is another aspect of knowledge engineering that is unique to the load expert system. The objective of this system is to be able to synthesize the load spectra. To do that, influence models and scaling models are required to generate the spectra for different loads. Rocketdyne's experts on these areas have helped us to design the models. A good example is the influence model implemented in the load expert system. The influence model calculates the dependent load gains based on the changes on a set of independent load gains. The model is used routinely by the engine performance analysts to evaluate the SSME engine performance for our customer. It turns out that this is the back bone model of the load expert system's load synthesis modules. The deterministic influence model devised by the engine performance analysis group coupled with the probability method RASCAL (the ANLOAD module) becomes the probabilistic influence model implemented in ANLOAD.

A very simple working memory model was built into the expert system, which serves as a carrier of communication between the rule modules. This model automates many expert system consultation tasks by passing information from rule module to rule module. Without it, the expert system has to rely on the users to supply the needed information.

With the system, we have managed to build intelligence into the system. In rule module RBLIDP, it knows how to select the most influential independent loads for a given dependent load and passes the information back to the other module which requests it. The system also facilitates the incremental building of the knowledge base with the data driven programming technique. When new information are added into the knowledge base, no existing module of the load expert system needs to be modified. Only new rule modules are built to utilize the new information and interact with the existing rules.

The knowledge-base for LDEXPT includes the following databases:

LIDP : the independent load information
LDEP : the dependent load information
LTBC : the turbine blade component pressure load information
LCTH : the component thermal load information
INFC : the influence coefficient set and gain value database
ICTH : the thermal load gain database
SCTH : the thermal load scaling model information
DFAT : the duty-cycle-data (engine flight and test data) information

The data contents of the database are presented in the load expert system manual.

6.4 Rule Modules

The load expert system LDEXPT is a rule-based expert system using a decision tree inference algorithm. The rules have the IF... THEN... format. The rules are built into a decision tree, one for each rule module. The branching of the tree is based on the user's response to the query or based on the information passed by the working memory from another rule module. This algorithm is very effective for implementing process control tasks. The domain knowledge of the composite load spectra project includes the load information and load models for load spectrum generation, and the knowledge of what to do with the load information and the load models in order to advice the user the procedure he/she has to take. An example of the later knowledge written in rule form can be as follows:

Rule #1
IF the user wants to do an deterministic influence model calculation for dependent load X,
THEN the user can select the rule module RBSICM for the calculation, where the user needs to select a number of independent loads and their variations off their nominal values.

Rule #2
IF the user does not know what independent loads are needed for the influence model calculation,
THEN the user can rely on the expert system to select the independent loads by selecting the ESASSIS option when prompted by the expert system.

Rule #3
IF the user does not know what variations of the independent loads are for the influence model calculation,

THEN the user can guess a percentage number, a recommended number would be 5% of the nominal value of that independent load, or it is best to do a probabilistic influence model calculation using the QLM (quick look model) rule module.

Rule #4
IF the user does not know what the quick look model (QLM) is, THEN the following will explain it: the quick look model is used to do an influence model calculation of a dependent load based on influences of a set of independent loads. The dependent load and the independent loads are all assumed to be normally distributed random variables. The variance of the dependent load is a sum of the variances of the independent loads multiplied by the squares of the corresponding influence coefficients.

Rule #5
IF the user wants to do a quick look model (QLM) calculation, THEN the user can call the RBQLM rule module. The user will need to select the independent loads for the calculation or depend on the expert system to select them using the ESASSIS option when prompt.

There are other kinds of rules that are needed for the load expert system. These rules are related to expert's knowledge about the loads. For example, it is known that the variances of loads, independent loads or dependent loads, consists of the time slice variance, test to test variance and engine to engine variance. These kinds of information are being acquired from the engine data. How the knowledge is used needs to be extracted from our experts. This will include rule of which variance is needed for a certain calculation, rule of what combination of the three types of variances is needed, etc.

Rules like explaining a procedure to the user and giving advise have not yet been built into the load expert system. The plan is to build more of such rules so that a novice of the load expert system can learn how to do load spectra calculation from the rules provided in the system.

The rules that are in the load expert system are mainly for database retrieval and process controls for different load model calculations. One rule module is for preparing an ANLOAD (load calculation) module input file which can then be submitted to ANLOAD to carry out a full scale time dependent load calculation. The rule modules that have been built are:

SLIDPL: retrieve independent load information such as mean, variance and distribution type etc.

SLDEPL: retrieve dependent load information

SLTBCL: retrieve turbine blade component pressure load information

SLICGN: retrieve influence coefficients and gain values

SLDCD: retrieve duty-cycle-data (engine flight and test data)

QLM: perform a dependent load calculation with a quick look model

SICM: perform a deterministic influence model calculation

ANLDIN: prepare an ANLOAD input file for a load calculation

SSM: perform a simple scaling model for turbine blade pressure load

SLTHCL: retrieve component thermal load information

SLSCTH: retrieve component thermal load influence model information

SLICTH: retrieve thermal load and boundary load influence coefficients

Rules for the separate transient model calculation will be written. It will include a transient spike model and a simple Poisson transient spike arrival model. Rules for advising when it is necessary to include a transient calculation for the desired load spectrum will also be provided.

6.5 LDEXPT Operation

The load expert system, LDEXPT version 2.0, was installed on the NASA/LeRC's VM system. Its function is to synthesize the rocket engine component load spectra.

6.5.1 Start the Load Expert System

To run the expert system, one needs

(1) Request more virtual memory by executing a CP command:

```
CP DEFINE STORAGE 4096K
```

(2) Returns to the CMS:

```
CP IPL CMS
```

(3) Loading the graphic-3D package:

```
GRAPH3D
```

(4) Loading the load expert system:

```
LDEXPT
```

The LDEXPT command sets up the required files, loads the program and start running the program.

LDEXPT v2.0, the LoaD EXPerT system, is a menu driven program. It has two subsystems: RBMS (the Rule Base Management System) and KBMS (the Knowledge Base Management System).

6.5.2 The Load Expert System Consultation

To run an expert system consultation session

(1) Enter ?RBMS command to go to RBMS. A menu listed the available commands will appear.

(2) Enter ?EXDR command to start the consultation. A list of rule modules will appear on screen:

SLIDPL	:	Retrieve Independent Load Information
SLDEPL	:	Retrieve Dependent Load Information
SLICGN	:	Retrieve Influence Coefficients and Gains
SLTBCL	:	Retrieve Turbine Blade Component Pressure Load Scaling Model Information
SLDCD	:	Retrieve and Plot a Duty-Cycle-Data Profile
SLTHCL	:	Retrieve Component Thermal Load Information
SLSCTH	:	Retrieve Thermal Load Scaling Model and Influence Model Information
QLM	:	Quick Look Model for Evaluating Dependent Load
SICM	:	Deterministic Influence Coefficient Model
SSM	:	Simple Scaling Model for Evaluating the Turbine Blade Component Pressure Load
ANLDIN	:	Prepare ANLOAD Input File
EXIT	:	Exit the Expert System Driver

Select one of the module, e.g. QLM, the expert system will start the session by queries.

6.5.3 The Load Calculation

To run a full scale load spectra calculation, one needs to run the ANLDIN rule module to prepare an ANLOAD input file or prepare one manually. Then EXIT the expert system driver and back to the RBMS subsystem. Enter ?ANLD, the ANLOAD module (the load calculation module) will start running.

6.5.4 The Database System

The KBMS, the knowledge base management system, has two modules: DBMS (the database system) and DBIO (the data processing module). The database system is a simple flat file system. It has all the basic database operations such as creating a database, inserting and deleting a database record, etc.

To go to the database system, enter ?DBMS at the KBMS menu prompt. A list of database commands will appear on screen:

?DBCR : Create a database table
?DBCF : Create fields for a database
?DBBK : Build key data
?DBSL : Select database record(s)
?DBDL : Delete database record(s)
?DBDF : Display field and key names
?DBUP : Update (Add) database record(s)
?DBRD : Open a database file
?DBSV : Save an updated database
?DBLT : List all of a database's records
?DBLK : List all key variables of a database
?INLD : Input load ID & properties
?INFL : Input influence coefficients
?HELP : List available database commands
?RETN : Return to KBMS
?QUIT : Exit LDEXPT

Enter an appropriate command, e.g. ?DBSL, the program will carry out the desired database task. The ?INLD and ?INFL commands are not generic database functions. They are provided for the composite load spectra project to build the load knowledge base.

6.5.5 Component Load Scaling Models

The component load is the local load specifically for the component of interest such as turbine blade and LOX post. Component loads are normally sensitive to the geometry of the component. In this section, examples of the component loads that were implemented in the load expert system are described. The evaluation models and the related load information will be discussed.

HPFT Turbine Blade Component Pressure Loads

(1) The Turbine Blade Centrifugal Load (rpm)

The component ID is ITBCOM=1 and the component load ID is IBLOAD=1. The turbine blade centrifugal load as used here is a synonym of the turbine speed (rpm). The turbine speed is one of the dependent loads can be calculated with the influence model. Therefore, for the turbine blade centrifugal load the scaling coefficient is 1.0.

(2) The Blade Mid-Point Stage 1 Tangential Load (lbf/blade)
ITBCOM=1 & IBLOAD=2

The blade mid-point tangential load is the tangential force per blade (lbf/blade) acted on by the working fluid. The tangential load is scaled with the turbine torque which is a dependent load of the influence model. The scaling coefficient is obtained for the 100% (RPL) power level condition of which the blade mid-point stage 1 tangential load is 190 lbf/blade and the HPFT turbine torque is 9378 ft-lbf. The scaling equation is therefore,

$$Ft1 = 2.026e-2 * Torque$$

(3) The Blade Mid-Point Stage 2 Tangential Load (lbf/blade)
ITBCOM=1 & IBLAOD=3

It is the same as component load number 2 except this is for stage 2 rotor blade. The scaling load is the HPFT stage 2 turbine torque. The scaling coefficient is obtained for the RPL condition of which the blade mid-point stage 2 tangential load is 180 lbf/blade and the HPFT turbine torque is 9378 ft-lbf. The scaling equation is

$$Ft2 = 1.1919e-2 * Torque$$

(4) The Blade Mid-Point Stage 1 Axial Load (lbf/blade)
ITBCOM=1 & IBLOAD=4

The blade mid-point axial load is the axial force per blade acted on by the working fluid. The load is scaled with the pressure drop across the turbine, i.e. the pressure difference between the turbine inlet (pinlet) and the turbine outlet (poutlet). The turbine inlet pressure and the outlet pressure are assumed strongly correlated in this scaling model. The scaling coefficient is obtained for the RPL condition of which the turbine mid-point axial force is 140 lbf/blade and the pressure drop is 1423 psia.

Fa1 = 9.8384e-2 * (Pinlet-Poutlet)

(5) The Blade Mid-Point Stages 2 Axial Loads (lbf/blade)
ITBCOM=1 & IBLOAD=5

It is same as the component load number 4 but for stge 2 rotor. The scaling coefficient is obtained for the RPL condition of which the turbine mid-point axial force is 112 lbf/blade and the pressure drop across th turbine is 14223 psia.

Fa2 = 7.8707e-2 * (Pinlet-Poutlet)

(6) The Blade Distributed Stage 1 Tip Tangential Load (lbf/section)
ITBCOM=1 & IBLOAD=6

The blade distributed tip tangential load is the tangential force acted on the tip section of the turbine blade (lbf/section) which is divided into 7 equal cross sections. The scaling is the same as the component load number 2.

Ft1,tip = 2.8393e-3 * torque

(7) The Blade Distributed Stage 2 Tip Tangential Load (lbf/section)
ITBCOM=1 & IBLOAD=7

It is the same as component load number 5 above.

Ft2,tip = 1.66513-3 * torque

(8) The Blade Distributed Stage 1 Tip Axial Load (lbf/section)
ITBCOM=1 & IBLOAD=8

The blade distribution tip axial load is the axial force acted on the tip section of the turbine blade. The scaling is the same as the component load number 4.

Fa1,tip = 1.9024e-2 * (Pinlet-Poutlet)

(9) The Blade Distributed Stage 2 Tip Axial Loads (lbf/section)
ITBCOM=1 & IBLOAD=9

It is the same as component load number 7 above.

$$Fa2,tip = 1.522e-2 * (Pinlet-Poutlet)$$

(10) The Blade Distributed Stage 1 Mean Tangential Load (lbf/section)
ITBCOM=1 & IBLOAD=10

The blade distributed mean tangential load is the tangential force acted on the mean section of the turbine blade.

$$FT1,m = 2.8899e-3 * torque$$

(11) The Blade Distributed Stage 2 Mean Tangential Load (lbf/section)
ITBCOM=1 & IBLOAD=11

$$Ft2,m = 1.7002e-3 * torque$$

(12) The Balde Distributed Stage 1 Mean Axial Load (lbf/section)
ITBCOM=1 & IBLOAD=12

$$Fa1,m = 1.138e-2 * (Pinlet-Poutlet)$$

(13) The Blade distsributed Stage 2 Mean Axial Load (lbf/section)
ITBCOM=1 & IBLOAD=13

$$Fa2,m = 1.138e-2 * (Pinlet-Poutlet)$$

(14) The Blade Distributed Stage 1 Hub Tangential Load (lbf/section)
ITBCOM=1 & IBLOAD=14

The blade distributed hub tangential load is the tangential force acted on the hub section of the turbine blade.

$$F_{t1,hub} = 2.9654e{-3} * torque$$

(15) The Blade Distributed Stage 2 Hub Tangential Load (lbf/section)
ITBOM=1 & IBLOAD=15

$$F_{t2,hub} = 1.7446e{-3} * torque$$

(16) The Blade Distributed Stage 1 Hub Axial Load (lbf/section)
ITBCOM=1 & IBLOAD=16

$$F_{a1,hub} = 8.833e{-3} * (P_{inlet}-P_{outlet})$$

(17) The Blade Distributed Stage 2 Hub Axial Load (lbf/section)
ITBCOM=1 & IBLOAD=17

$$F_{a2,hub} = 7.0664e{-3} * (P_{inlet}-P_{outlet})$$

(18) The Blade Stage 1 Tip X-section Pressure Distribution
ITBCOM=1 & IBLOAD=18

The blade cross section pressure at a particular node on the circumference of the cross section can be evaluated as the sum of the cross section average pressure and the differential pressure between the pressure at the node and the average cross section pressure. In the scaling model, the cross section average pressure is scaled with the turbine inlet pressure. For the blade stage 1 tip cross-section average pressure the scaling coefficient is obtained at the RPL condition of which the average pressure is 5116.499 psia and the turbine inlet pressure is 5916 psia. The differential pressure term is scaled by the turbine torque which is at the RPL condition 10829.156 ft-lbf. A total of 33 nodes is used for this cross section in the database.

Pnode = 0.8649 * Pinlet + SC node * Torque.

(19) The Blade Stage 2 Tip X-section Pressure Distribution
ITBCOM=1 & IBLOAD=19

The load is the same as the component load number 18 above. A total of 40 nodes for this cross section is in the database.

Pnode = 0.6645 * Pinlet + SCnode * Torque

(20) The Blade Stage 1 Mean X-section Pressure Distribution
ITBCOM=1 & IBLOAD=20

It is the same kind of load for the mean cross-section as the component load number 18. The scaling model is the same.; 35 nodes are in the database.

Pnode = 0.8565 * Pinlet + SCnode * Torque.

(21) The Blade Stage 2 Mean X-section Pressure Distribution
ITBCOM=1 & IBLOAD=21

34 nodes are in the database.

Pnode = 0.6645 * Pinlet + SCnode * Torque.

(22) The Blade Stage 1 Hub X-section Pressure Distribution
ITBCOM=1 & IBLOAD=22

36 nodes are in the database.

Pnode = 0.8488 * Pinlet + SCnode * Torque.

(23) The Blade Stage 2 Hub X-section Pressure Distribution
ITBCOM=1 & IBLOAD=23

35 nodes are in the database.

Pnode = 0.6631 * Pinlet + SCnode * Torque.

The Turbine Blade Thermal Load

ITBCOM=1 & IBLOAD=25

The turbine blade thermal load model evaluates the turbine blade steady state temperatures of selected nodes on the blade for an engine condition. The model first evaluates a set of boundary conditions for the particular engine conditions using a thermal load influence model. For the turbine blade thermal load, the boundary condition loads are the maximum temperature and the minimum temperature of the blade, and the two isotherms that separate (1) the hot gas and the coolant, and (2) the two different coolant mixing regions in the shank area. The controlling dependent loads of these boundary loads are the turbine inlet (Tin) and discharge temperatures (Tout), the pump discharge temperature (Tp) and the two geometric factors accounting for the hot gas (Ga) and the coolant leakage (Gc) into the shank areas of the blade.

% of max.Twg = 0.8269*(% of Tout) + 0.1731*(% of Tin)

% of min.Twc = 0.2283*(% of Tp) - 0.7872*(% of Gc)

% of Tml = 0.00798*(% of Tp) - 0.0275*(% of Gc) + 0.8038*(% of Tout) + 0.1682*(% of Tin) + 1.0*(% of Gh)

% of Tm2 = 0.0563*(% of Tp) - 0.1942*(% of Gc) + 0.6639*(% of Tout) + 0.1389*(% of Tin) + 0.8259*(% of Gh)

where (% of Var) means the percentage change of the variable Var, i.e.

% of Var = (Var2 - Var1)/Var1

The thermal load model then evaluates the turbine blade temperatures with a scaling model. The reference temperatures used in the scaling model were generated by a 3D turbine blade thermal analysis at the FPL (109% power level) operating condition. The scaling equation is

$$\frac{T - Tb1}{Tb2 - Tb1} = \frac{Ref.\ T - Ref.\ Tb1}{Ref.Tb2 - Ref.\ Tb1}$$

where T is the temperature of a node on the blade to be evaluated,

(Ref. Tb1) < (Ref. T) < (Ref. Tb2),

(Ref. Tb1) and (Ref. Tb2) are the boundary conditions for the region of interest,

the reference maximum blade temperature Ref. max.Twg = 1860°R,

the reference minimum blade temperature Ref. min.Twc = 399°R,

the reference first mixed gas temperature Ref. Tm1 = 1660°R, and

the reference second mixed gas temperature Ref. Tm2 = 1005°R.

The HGM Fuel Center Transfer Tube Thermal Load
ITBCOM=5 & IBLOAD=25

The HGM (Hot Gas Manifold) fuel center transfer tube thermal load model was implemented the same way as the turbine blade thermal model. The boundary condition loads for the influence model are the maximum tube wall temperature S(max. Twg)and the minimum tube wall temperature (min.Twc). The controlling dependent loads are the hot gas temperature and the coolant temperature (Tc).

% of max.Twg = 0.99962*(% of Tg)

% of min.Twc = 0.99432*(% of Tc)

The scaling is done the same way as the turbine blade thermal model.

$$\frac{T - \text{min.Twc}}{\text{max.Twg} - \text{min.Twc}} = \frac{\text{Ref. } T - \text{Ref. min.Twc}}{\text{Ref. max.Twg} - \text{Ref. min.Twc}}$$

where T is the temperature of a node on the transfer tube to be evaluated,

the reference maximum wall temperature Ref. max.Twg = 1558.5°R, and
the reference minimum wall temperature Ref. min.Twc = 494.9°R

REFERENCES

1. NASA CR-179496, Composite Load Spectra for Select Space Propulsion Structural Components, First Annual Report, March 1986

2. NASA CR-TBD, Composite Load Spectra for Select Space Propulsion Structural Components, Second Annual Report

3. Faddeeva, V.N., "Computational Methods of Linear Algebra," Dover Publications, 1959.

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13. ABSTRACT ***(Maximum 200 words)***
The objective of this program is to develop generic load models with multiple levels of progressive sophistication to simulate the composite load spectra that are induced in space propulsion system components, representative of Space Shuttle Main Engines (SSME), such as transfer ducts, turbine blades, and liquid oxygen (LOX) posts and system ducting. These models will be developec using two independent approaches. The first approach will consist of using state-of-the-art probabilistic methods to describe the individual loading conditions and combinations of these loading conditions to synthesize the composite load spectra simulation. Th methodology required to combine the various individual load simulation models (hot-gas dynamic, vibrations, instantaneous positio centrifugal field, etc.) into composite load spectra simulation models will be developed under this program. A computer code incorporating the various individual and composite load spectra models will be developed to construct the specific load model desir The second approach, which is covered under the options portion of the contract, will consist of developing coupled models for composite load spectra simulation which combine the (deterministic) models for composite load dynamic, acoustic, high-pressure a high rotational speed, etc., load simulation using statistically varying coefficients. These coefficients will then be determined using advanced probabilistic simulation methods with and without strategically selected experimental data. This report covers the efforts the third year of the contract. The overall program status is that the turbine blade loads have been completed and implemented. Th transfer duct loads are defined and are being implemented. The thermal loads for all components are defined and coding in work. dynamic pressure load model is under development. The parallel work on the probabilistic methodology is essentially completed. overall effort is being integrated in an expert system code specifically developed for this project.

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